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**DESIGN OF THERMAL PROTECTION SYSTEMS FOR  
LIQUID HYDROGEN TANKS**

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**LIQUID PROPELLANT  
LOSSES DURING  
SPACE FLIGHT**

DESIGN OF THERMAL PROTECTION SYSTEMS  
FOR LIQUID HYDROGEN TANKS

Technical Report

to

The National Aeronautics and Space Administration  
(NASA Contract Number NAS 5-664, NASw-615)

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## PURPOSE AND SCOPE

This report gives an account of the progress achieved in the design, experimental measurement and analysis of thermal protection systems for liquid hydrogen tanks. This work is being carried out by Arthur D. Little, Inc., under contract NAS5-664 and continuation contract NASw-615, at Cambridge, Mass., and at NASA Lewis Research Center, Cleveland, Ohio. Supplements to data presented in this report will be issued as significant new results are obtained.

The objectives of the work are the following:

1. Provide data to guide the design of efficient thermal protection systems for cryogenic fuel tanks for use in extended space missions with primary emphasis placed on multilayer insulations for liquid hydrogen tanks.
2. Establish design parameters adequate to meet production requirements, pre-flight check out, and mission objectives to assure highest insulating effectiveness.
3. Measure the thermal performance of typical multilayer insulations consisting of materials within the present state of the art.

## I. INTRODUCTION

The brilliantly glowing nose cone successfully resisting the effects of aerodynamic heating while re-entering the earth's atmosphere is proof that thermal protection systems can be developed to meet conditions which only a few years ago were beyond technological feasibility. Less spectacular, but of equal importance to the continued progress of space exploration, is the development of thermal protection systems for cryogenic fuels, in particular liquid hydrogen, to meet the demands of a wide spectrum of space missions. The difficulties that impede thermal protection development and application have only recently been fully appreciated after it was demonstrated that thermal insulations and application techniques cannot be relegated to the category of engineering design details. The principal challenge lies in the integration of advanced cryogenic insulations with the advancing state of the art of shell-tank design.

Thermal protection systems adequate to meet the demands of fuel conservation for space missions which may last more than a few days are not within the present state of the art. The development efforts required before liquid hydrogen tanks can be adequately insulated to permit space vehicles to explore the regions beyond the vicinity of the earth appear to be at least equivalent to efforts already expended on the development of nose-cone materials.

The following discussion deals with the requirements of thermal protection systems subjected to ground and space environments; typical materials, either presently available or under development; the influence of the physical variables governing the thermal properties of those materials and the apparatus required for their measurement; possible improvements in thermal protection systems; and design considerations for thermal protection systems, dictated by production, handling, and test requirements.

## II. ENVIRONMENTS AFFECTING THERMAL PROTECTION SYSTEMS

From the time a thermal protection system is assembled in the production plant to the successful completion of its mission, it will have been exposed to a number of environmental interactions which need to be recognized and considered in the various design approaches and performance expectations.

### II-A. THERMAL INTERACTION

A thermal protection system has to be designed to reduce the boil-off rate caused by heat sources external to the vehicle and by heat sources on-board. Among the external heat sources are the thermal conditions existing on the ground prior to flight, the aerodynamic heating encountered during boost, and the various radiation heat inputs--such as direct solar radiation and planet shine--modified by possible vehicle orientation. On-board heat sources consist of radiative inputs from other portions of the vehicle and heat leaks to the propellant tank from supports, pipes and other structural members.

### II-B. IONIZING RADIATION INTERACTIONS

The ionizing radiation existing in a space environment may affect the performance of thermal protection system materials, particularly those of organic origin.

### II-C. METEOROID INTERACTIONS

Destructive effects due to meteoroids of high kinetic energy can markedly reduce the effectiveness of thermal protection systems unless suitable meteoroid protection systems to mitigate these effects are employed.

### II-D. MECHANICAL INTERACTIONS

The handling and transportation of the insulated tanks prior to firing may place severe restrictions on the design of thermal protection systems so as not to decrease reliability and not to increase the complexity of maintenance procedures. It is in this area that increased communication between designers and producers is required so that designers may take into account human errors which could result in damage to the thermal protection system.

### III. SELECTION OF MATERIALS FOR THERMAL PROTECTION SYSTEMS

#### III-A. GENERAL CRITERIA

For liquid-hydrogen-fueled vehicles on extended space missions, a thermal protection system is essential. However, considerable choice can be exercised in the combination and selection of materials for a system based on meeting the conditions imposed by the above environment. The thermal performance, thickness, and weight of insulation materials have to be optimized to accomplish a specific mission so as to minimize weight penalties.

For example, weight penalties can be associated with different methods for preserving a cryogenic fuel depending on whether vented storage or non-vented storage, with or without a refrigerator, is being used. (1) Figure III-A1 illustrates the effect of these different methods on the thickness of high efficiency insulation required for a given stay-time in space for liquid hydrogen tanks of different diameters. Although refrigeration can be seen to greatly reduce the thickness requirement, thereby leading to a several-fold reduction in weight penalties for extended stay-times, a finite insulation thickness is still essential.

Figure III-A2 compares the thermal conductivity of insulating materials applicable to thermal protection systems. Although there is nearly a three-order-of-magnitude difference in the insulating effectiveness of these various materials, their strength properties, temperature capabilities, application feasibility and cost have to be considered before including these materials in a thermal protection system.

The following review presents the salient characteristics of thermal insulators which are of particular interest in a thermal protection system for liquid hydrogen tanks.

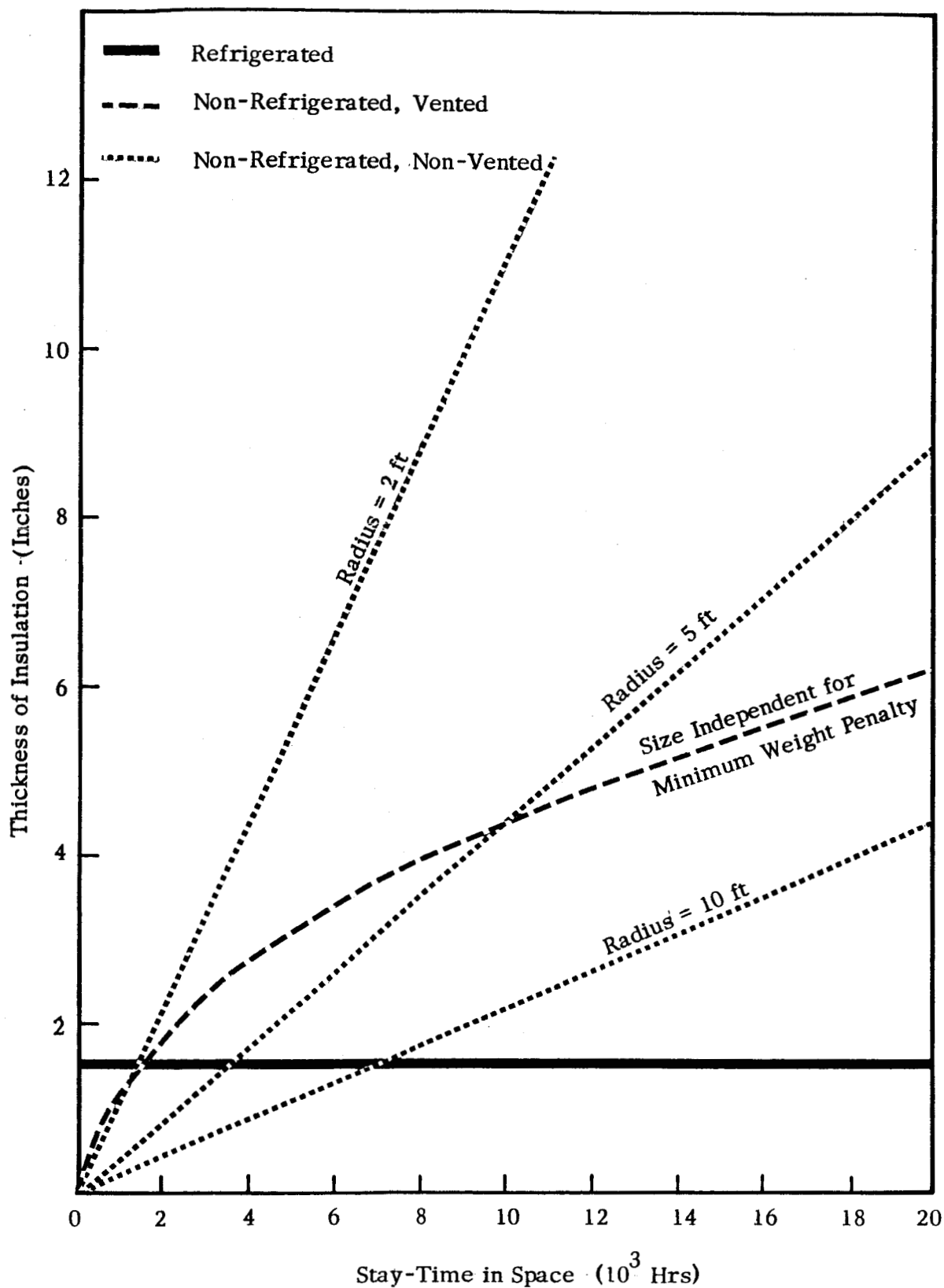


FIGURE III-A1 COMPARISON OF INSULATION REQUIREMENTS FOR ALTERNATE METHODS OF STORING LIQUID HYDROGEN

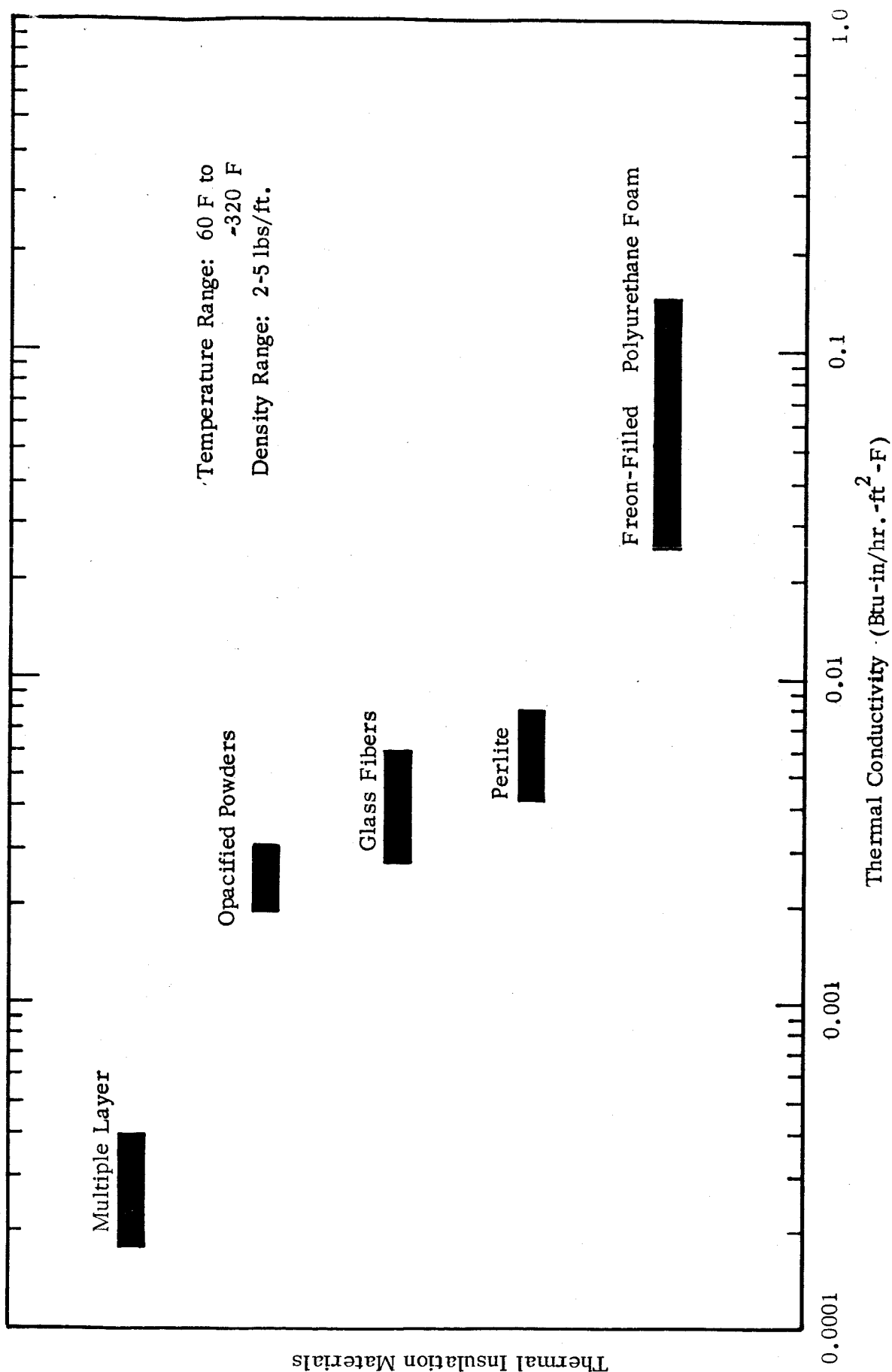


FIGURE III-A2 THERMAL CONDUCTIVITY OF TYPICAL THERMAL INSULATORS

### III-B. FOAMS

Great strides have been made in the development of various types of foamed organic plastics using either fluorinated hydrocarbons or carbon dioxide as expanding agents. The thermal conductivity of foams as a function of temperature and the effect of foam structure on thermal conductivity are useful criteria of the insulating effectiveness of foams.<sup>(2)</sup> Figure III-B1 shows the dependence of thermal conductivity on temperature for a Freon expanded foam of two lb/cu ft density. The non-linearity in this dependence appears to be due to increased heat transfer by convection currents resulting from re-boiling of condensed Freon and to increased heat transfer by conduction because of the saturation of the foam-cell surfaces with liquid Freon. Furthermore, the addition of heat to the warmer side of the foam cell may cause a mass transfer of saturated Freon vapor to the cold side with subsequent release of latent heat. This behavior will be of particular interest when the foam is to be used in combination with other thermal insulators.

Figure III-B2 illustrates the effect of foam cell size on thermal conductivity and indicates that the smaller the cell diameter the greater the resistance to heat flow because of the increased heat flowpaths per unit thickness.

Foam insulation becomes a partially evacuated insulation when it is exposed to liquid hydrogen, because of cryopumping effects. Thus precautions have to be taken to assure that gas-tight barriers are provided to stop the penetration of moisture and air into the insulation, which would result in a marked increase in thermal conductivity and the possible disruption of the cells if surface temperature suddenly increased. In addition, an explosion hazard would be created if hydrogen leaked from the tank and came in contact with any condensed air. To reduce this hazard, a helium purge can be introduced to carry away any diffusing atmospheric gases. The helium purge will, however, lead to a substantial decrease in insulating effectiveness of the foam.

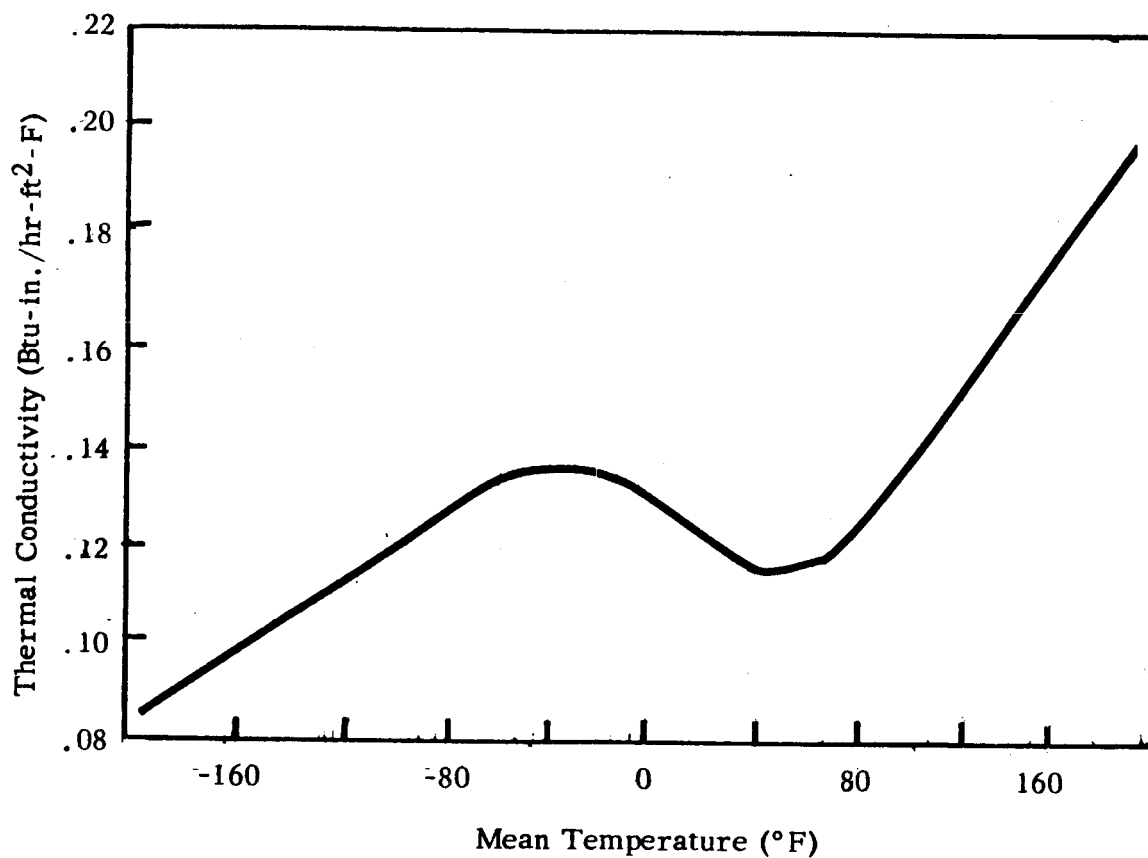


FIGURE III-B1 THE DEPENDENCE OF THERMAL CONDUCTIVITY ON TEMPERATURES OF FREON EXPANDED POLYURETHANE FOAM

Source: R. E. Knox, "Insulation Properties of Fluorocarbon Expanded Rigid Urethane Foam"

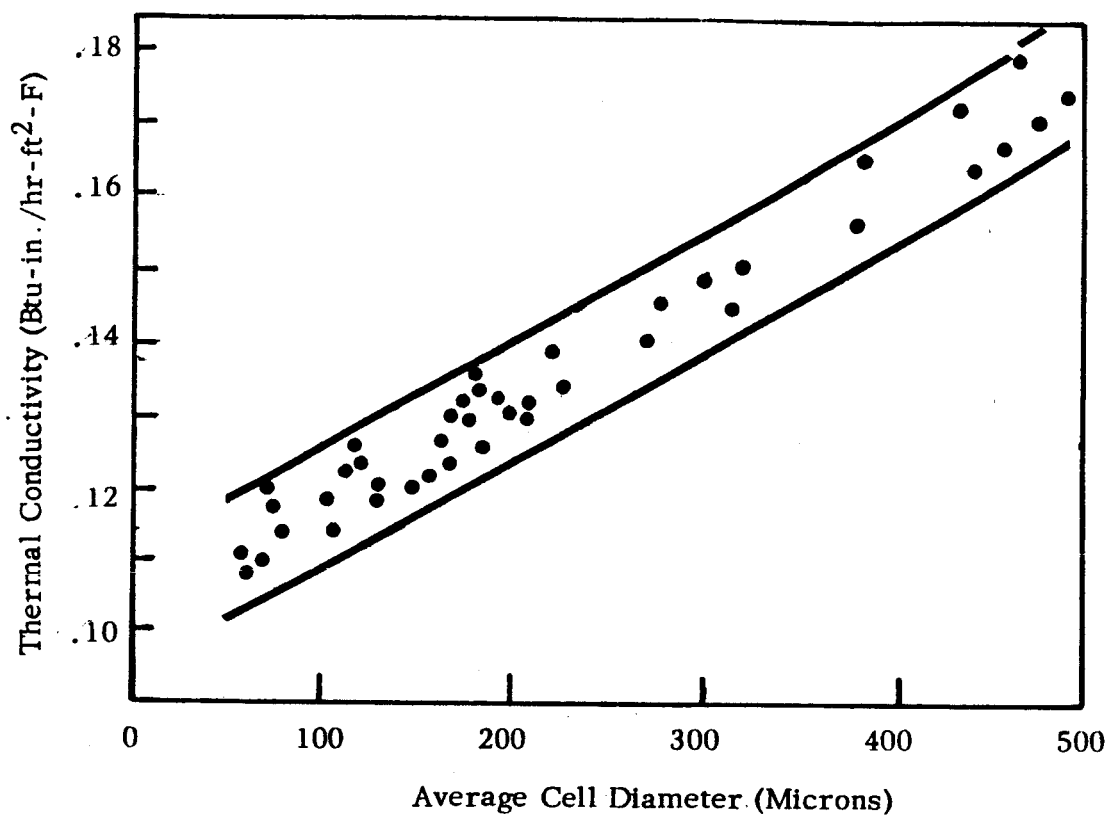


FIGURE III-B2 THE EFFECT OF CELL SIZE OF FREON EXPANDED POLYURETHANE FOAM ON THERMAL CONDUCTIVITY

Source: R.E. Knox, "Insulation Properties of Fluorocarbon Expanded Rigid Urethane Foam"

### III-C. POWDERS AND FIBERS

Powder and fiber insulations have a low thermal conductivity when gases have been removed from the void spaces. As far back as 1910, it was recognized that thermal insulators far more effective than air could be obtained by subjecting finely divided materials to a vacuum.<sup>(3)</sup> Although remarkable improvements are obtained by the removal of gas, other heat transfer mechanisms must also be minimized. Heat flow through an evacuated insulating material can be attributed to the simultaneous operation of several different mechanisms:

- (1) Solid conduction through the materials making up the insulation and conduction between the particles across areas of contact,
- (2) Residual gas conduction in spaces between the particles, and
- (3) Radiation across the spaces between and through the particles.

Solid conduction can be reduced by breaking up the conduction paths through the use of finely divided materials so that resistances to heat flow are formed at the surface of each particle or fiber. To maintain these devious heat flow paths, the contact areas between the individual particles must be reduced to point contacts. These resistances are a function of the load imposed on the material and depend upon the amount of deformation at such point contacts. The particle size of a specific powder or the diameter of the fiber will influence the area of contact as well as the resistance per unit thickness of insulation. It is also desirable that the void spaces between particles be small enough so that gas conduction can be greatly reduced at reasonably low pressures. Therefore, with powders a range of particle sizes are desirable so that large voids are filled by smaller particles and small voids, in turn, by still smaller particles. Submicron fibers parallel to each other and normal to the heat flow path tend to exhibit an increased insulating effectiveness.

Evacuated insulating materials require that most of the gas be removed to obtain the desired insulating effectiveness; the degree of vacuum necessary to achieve this is of great practical importance. The mechanism by which heat flows, by means of gas conduction, between the particles can be explained on the basis of the kinetic theory of gases. The effect of gas conduction can be divided into two separate regions:

- (1) The region ranging from atmospheric pressure down to a few millimeters of mercury, in which gas conduction is independent of pressure.
- (2) A region at pressures below a few millimeters of mercury, in which gas conduction depends on pressure.

The transition from one conduction region to the other depends upon the mean diameter of the powder or fiber, the arrangement of individual particles, and the pressure required to obtain a specific mean-free path. When the mean free path of the gas molecules is greater than the distance between the individual particles, the pressure-dependent region is obtained. The thermal conductivity of the gas at that point decreases substantially until a lower limit is obtained at a pressure when most of the gas molecules have been removed. The larger the particle spacing, the lower the pressure required for the thermal conductivity to approach its limiting value. Figure III-C1 illustrates the dependence of thermal conductivity on pressure for various particle spacings. At low pressures, the thermal conductivity still has a finite value because heat can be transferred by radiation, by solid conduction within and through the particles, and by residual gas conduction. The effect of residual helium or nitrogen gas on thermal conductivity of perlite is shown in Figure III-C2<sup>(4)</sup> and on multilayer insulations in Figure III-C3.

Fine powders and sub-micron diameter fibers exhibit a very low solid conductivity, but they are relatively transparent to radiation. The radiation heat-transfer component in powders can be reduced by the addition of absorbing and scattering media, such as metallic flakes or carbon powder.<sup>(5)</sup> Figure III-C4 shows the effect of the addition of aluminum flakes on thermal conductivity.<sup>(6)</sup> The addition of larger amounts of opacifiers tends to increase solid conduction; therefore, there is a limit to the improvement that can be obtained by this technique.

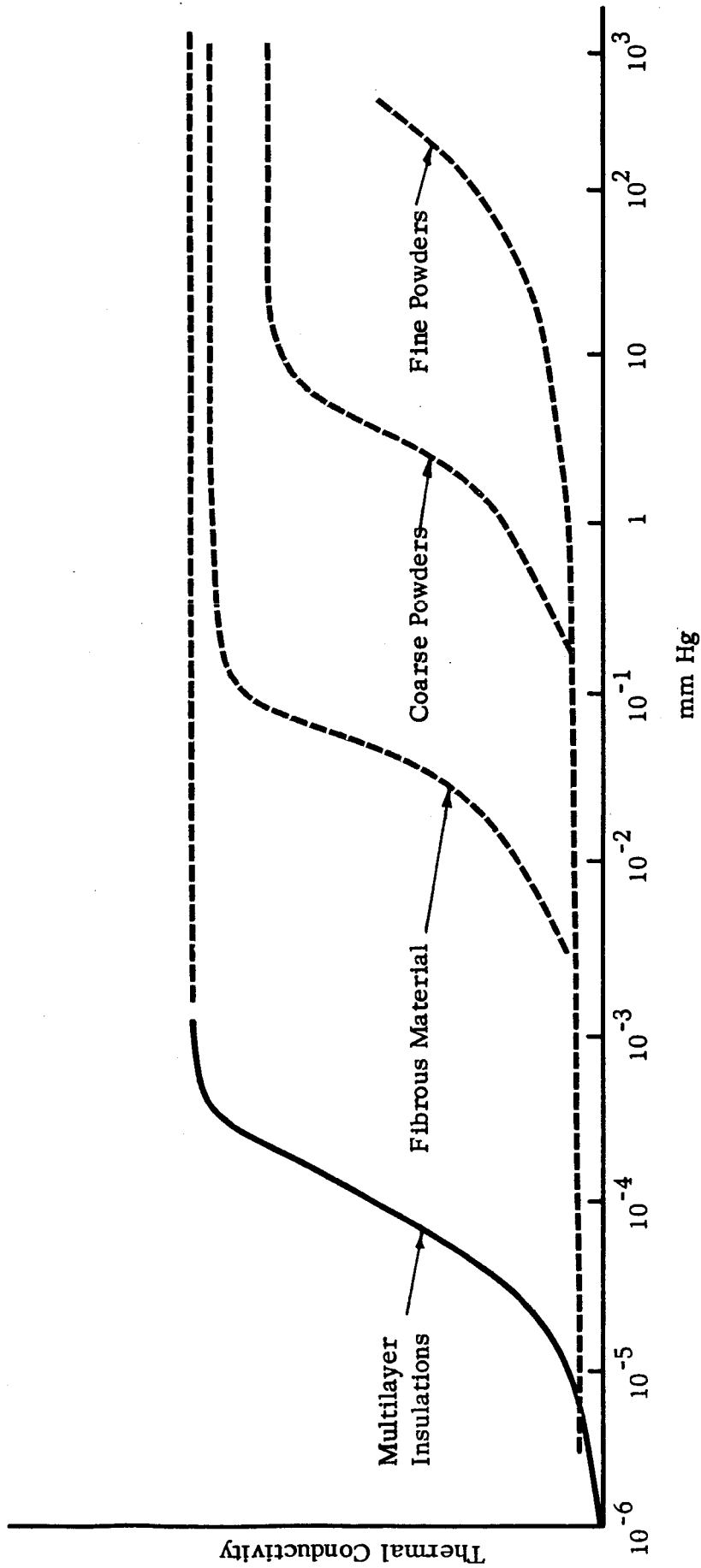


FIGURE III-C1 DEPENDENCE OF THERMAL CONDUCTIVITY ON PRESSURE FOR VARIOUS PARTICLE SPACINGS

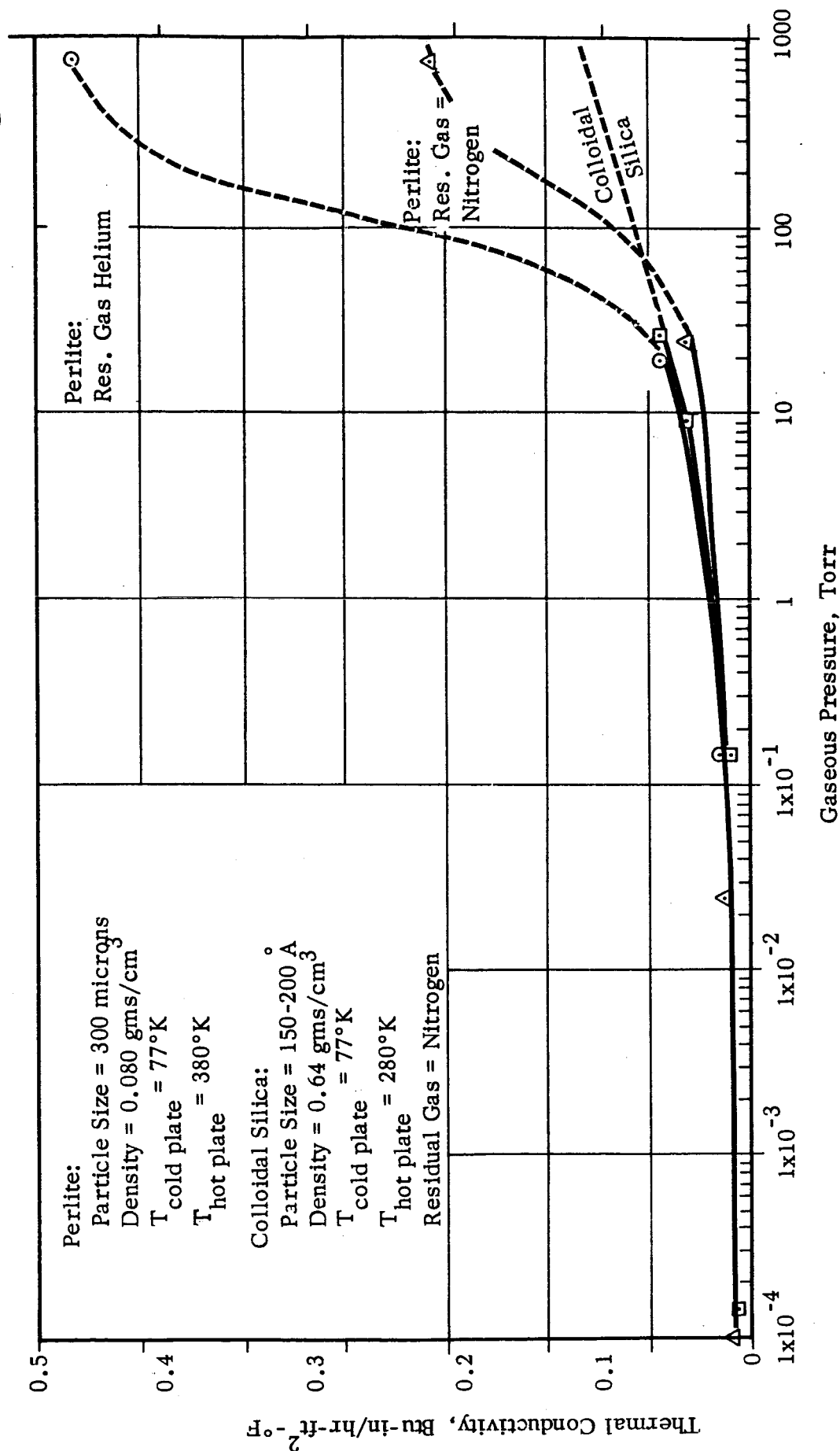


FIGURE III-C2 EFFECTS OF PRESSURE AND RESIDUAL GAS ON THERMAL CONDUCTIVITY OF COLLOIDAL SILICA AND PERLITE

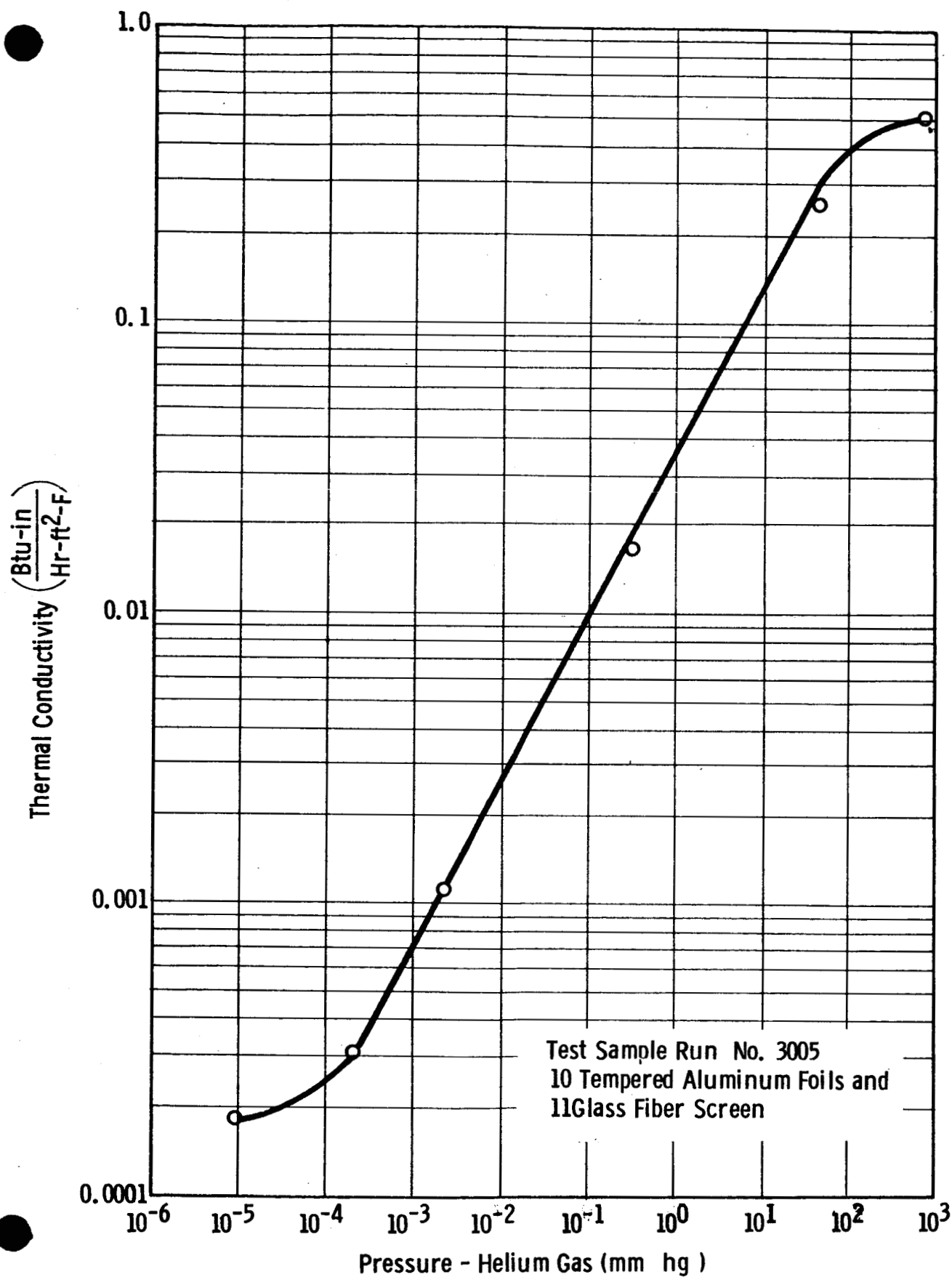


FIGURE III-C3 THE EFFECT OF HELIUM ON THERMAL CONDUCTIVITY OF MULTILAYER INSULATION

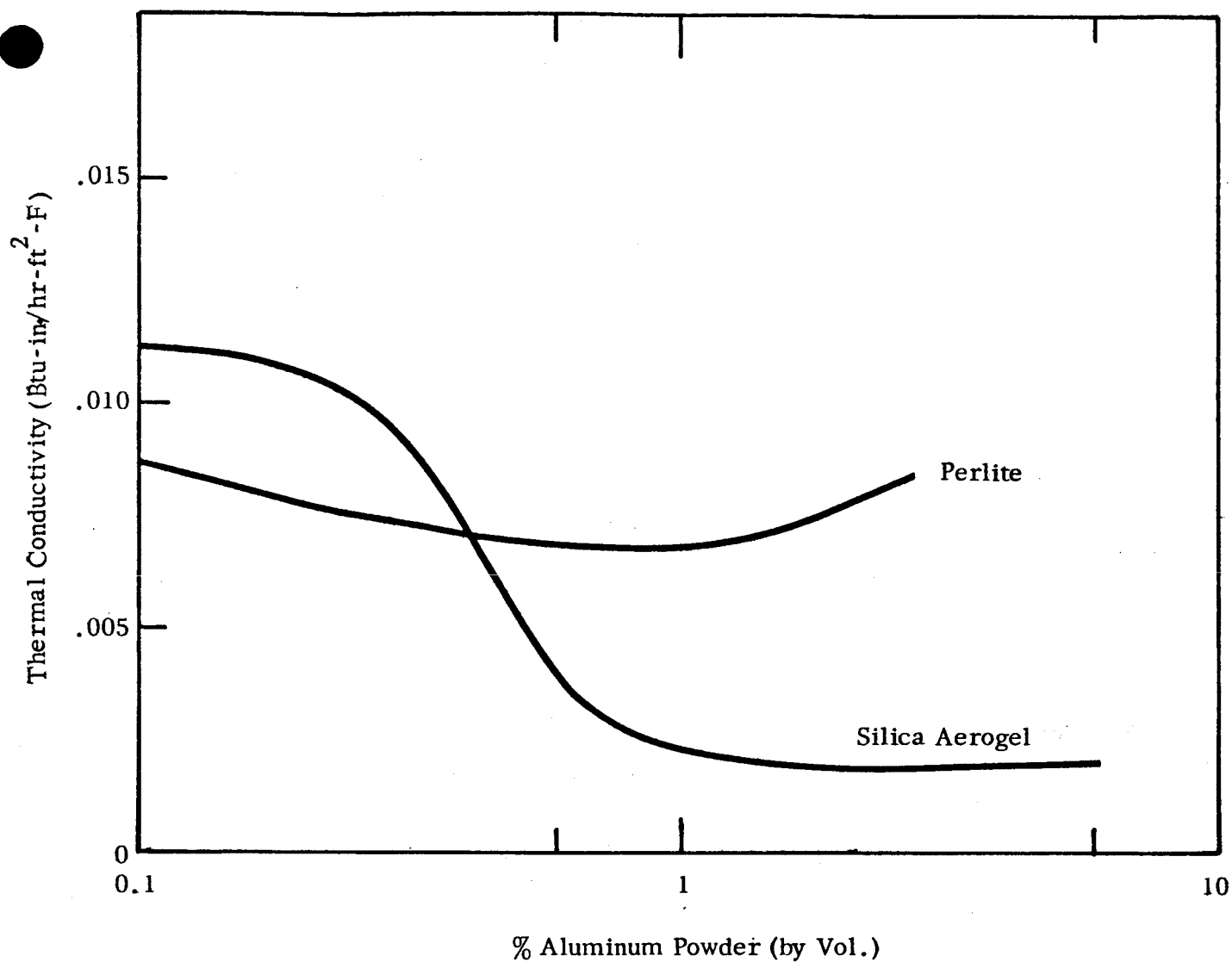


FIGURE III-C4 THE EFFECT OF ADDITION OF ALUMINUM POWDER ON THERMAL CONDUCTIVITY OF PERLITE AND SANTOCEL

Source: D. Cline and R.H. Kropschot, "Thermal Properties of Powder Insulations in the Temperature Range 300° to 4°K"

### III-D. MULTILAYER INSULATION

The work on multilayer insulations carried out by Peterson<sup>(7)</sup> and the further improvements carried out by researchers in this country<sup>(8, 9, 10)</sup> have resulted in an insulating effectiveness substantially better than that achieved with evacuated powders and fibers. In this type of insulation, the principles already used in the improvement of evacuated insulation were carried to their logical conclusion by the recognition of the importance of radiation heat transfer once the mechanisms of gas conduction and solid conduction have been reduced. Ideally, in this insulation, radiation shields of the highest reflectivity are separated by nearly nonconducting spacers in a high vacuum. The term superinsulation has been applied to this insulation system to signify the importance of this technological advance. Table III-D1 lists typical multilayer insulations which have been tested in this program. Other material combinations will be investigated as they become available.

The successful application of multilayer insulations to the solution of cryogenic storage and transportation problems of large cryogenic tanks on earth points to the promising solution of the problem of thermal protection of liquid hydrogen during long periods of space travel. However, before multilayer insulations can be incorporated in a thermal protection system, a number of basic problems will have to be solved. This task is more difficult than first realized, because of the many variables which influence the effectiveness of multilayer insulations, and the difficulties of translating the results of laboratory experience into production techniques.

TABLE III-D1TYPICAL MULTILAYER INSULATIONS

<u>Test and Sample No.</u>	<u>Radiation Shield</u>	<u>Spacer</u>
1005 1035	0.002-inch thick H-19 tempered aluminum, bright on two sides (Alcoa)	0.020-inch thick vinyl-coated glass fiber screen, grid dimensions 1/8 x 1/8 inch (Owens Corning)
1031	0.00025-inch thick crinkled polyester film, aluminized on one side (NRC)	0.020-inch thick vinyl-coated glass fiber screen, grid dimensions 1/8 x 1/8 inch (Owens Corning)
1032	0.002-inch thick H-19 tempered aluminum, bright on two sides (Alcoa)	0.008-inch thick glass fiber mat (Dexter Paper) with 50 percent perforations
2005	0.00025-inch thick crinkled polyester film, aluminized on one side (NRC)	0.001-inch thick glass fiber cloth (J. P. Stevens)
3001	0.00025-inch thick crinkled polyester film, aluminized on one side (NRC)	
1033	0.00025-inch thick crinkled polyester film, aluminized on one side (NRC)	0.008-inch thick glass fiber mat with 50 percent perforations (Dexter Paper)
2006	0.0005-inch thick soft aluminum bright on one side (Alcoa)	0.003-inch thick polyester fiber spacers (Dextex Paper)

## IV. THERMAL CONDUCTIVITY MEASUREMENTS

### IV-A. TYPES OF APPARATUS

As part of the work which has been undertaken by Arthur D. Little, Inc., to investigate liquid propellant losses in space,<sup>(11)</sup> a number of the variables which influence the performance of multilayer insulation under projected use conditions are being investigated.

The variables influencing insulation performance which are of particular interest are the following: (1) temperature, (2) gas pressure, (3) outgassing of foils or spacers, (4) mechanical pressure, (5) emittance, and (6) the effects of thermal shorts and discontinuities.

To permit experimental measurement of the influence of these variables, a suitable thermal conductivity apparatus had to be constructed. Several basic designs for thermal conductivity apparatus have been used for investigations of specific variables.<sup>(12)</sup> None of them is standard or capable of meeting all the required test conditions for the measurement of the above variables. The designs presently in use can be classified, according to the shape of the sample test chamber, as spherical, cylindrical, or flat plate. Spherical and cylindrical designs are discussed in Appendix A. Two flat plate designs, the guarded hot plate and the single-guarded cold plate, are also discussed in Appendix A. This section describes a third type of flat plate apparatus and the results obtained with it.

#### IV-B. DOUBLE-GUARDED COLD PLATE APPARATUS

Figure IV-B1 shows the design details of the apparatus, which consists of the following major components: a measuring vessel enclosed in a ring-shaped guard vessel, an outer guard jacket which can be filled with liquid nitrogen while the other vessels are filled with liquid hydrogen, a warm plate on which the sample is placed, and a sample chamber which allows for control of the atmosphere and pressure surrounding the sample separate from that of the bell jar enclosing the rest of the apparatus. Figure IV-B2 shows a photograph of the assembled apparatus.

The apparatus is designed to measure the thermal conductivity of any multilayer insulation, powder, fiber, or foam whose thermal conductivity is as low as  $10^{-4}$  Btu-in./hr-ft<sup>2</sup>-F. With minor modifications, emissivities of these materials can also be measured.

Figure IV-B3 shows the instrumentation which is required to carry out sensitive heat flow measurements. Because the measurement of heat flow relies on the measurement of the boil-off rate from the cryogenic fluid in the measuring vessel, the volume of gases boiled-off can either be measured with a gas flow meter or, for very low boil-off rates, by collecting gases above a low vapor pressure oil in a graduate.

The apparatus is designed so that one side of the sample can be exposed over a range of discrete temperatures from 4.2 to 243°K depending on the boiling point of the specific fluid used. The other side of the sample can be exposed to a range of temperatures from 20 to 500°K by proper choice of fluids and automatic temperature control. The test sample, in the form of a disc, can range in thickness from 0 to 2 inches, with diameters from 6 to 12 inches. The measuring section of the sample is 6 inches in diameter. The sample can be exposed to any desired gas pressure from  $10^{-6}$  Torr up to one atmosphere. In addition, the test chamber can be filled with different gases while a test is in progress. The sample thickness can be changed during a test by moving the hydraulically actuated warm plate. Three dial indicators permit the parallel alignment of the warm and cold plates and the thickness of the test sample to be checked during the test within an accuracy of 0.001 inch. While the test is in progress, mechanical pressure from 0 to 50 psi can be applied to the sample by a hydraulically controlled and calibrated pressure unit. During a test, control can be exercised over the temperatures of the side walls of the sample chamber to control edge effects. A guard shield can be placed in thermal contact with a low-temperature cryogenic cooled plate or can be heated by an electric heater should this be desirable.

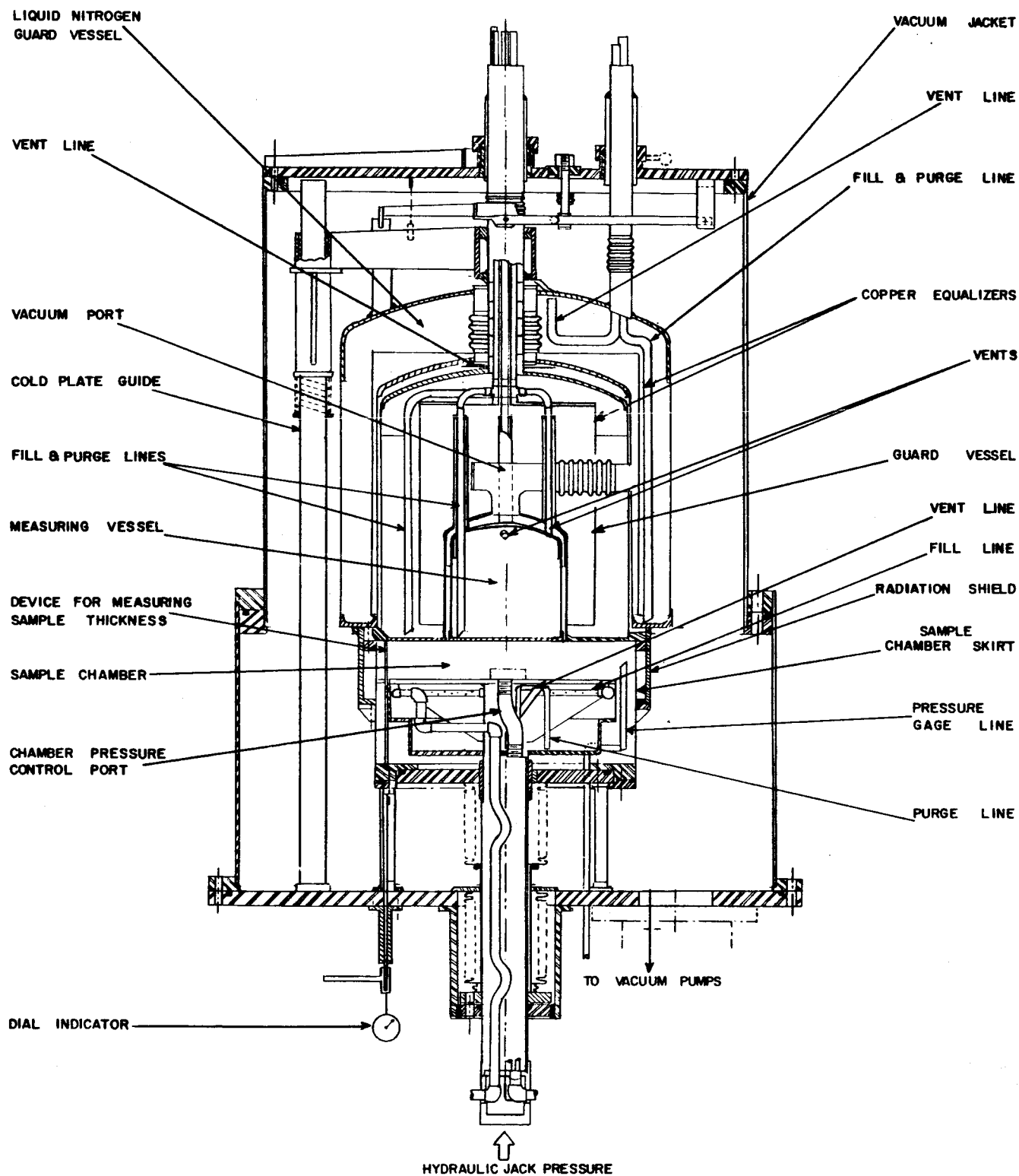


FIGURE IV-B1 DIAGRAM OF THE DOUBLE-GUARDED COLD PLATE THERMAL CONDUCTIVITY APPARATUS

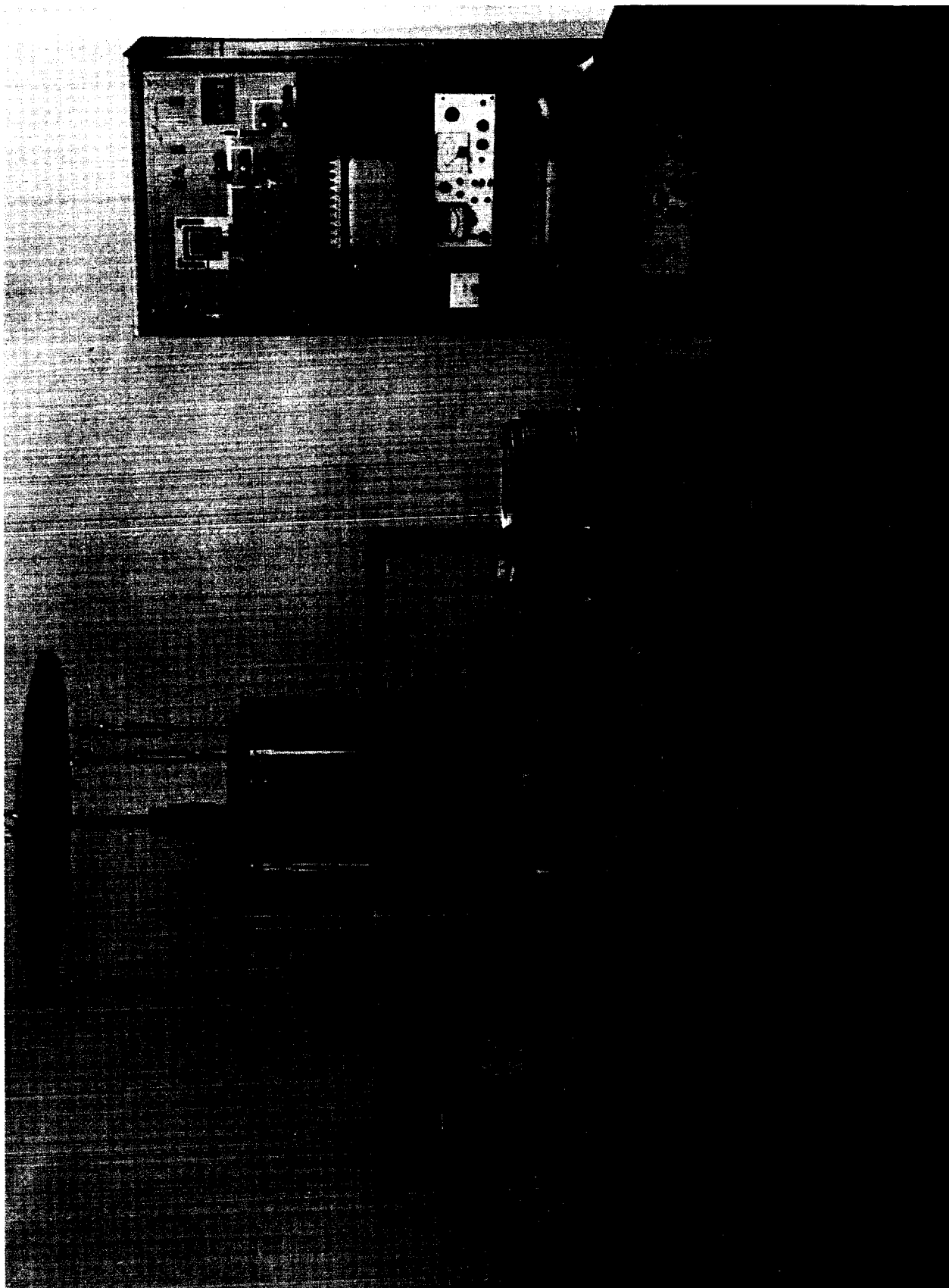


FIGURE IV-B2 ARRANGEMENT OF DOUBLE-GUARDED THERMAL  
CONDUCTIVITY APPARATUS

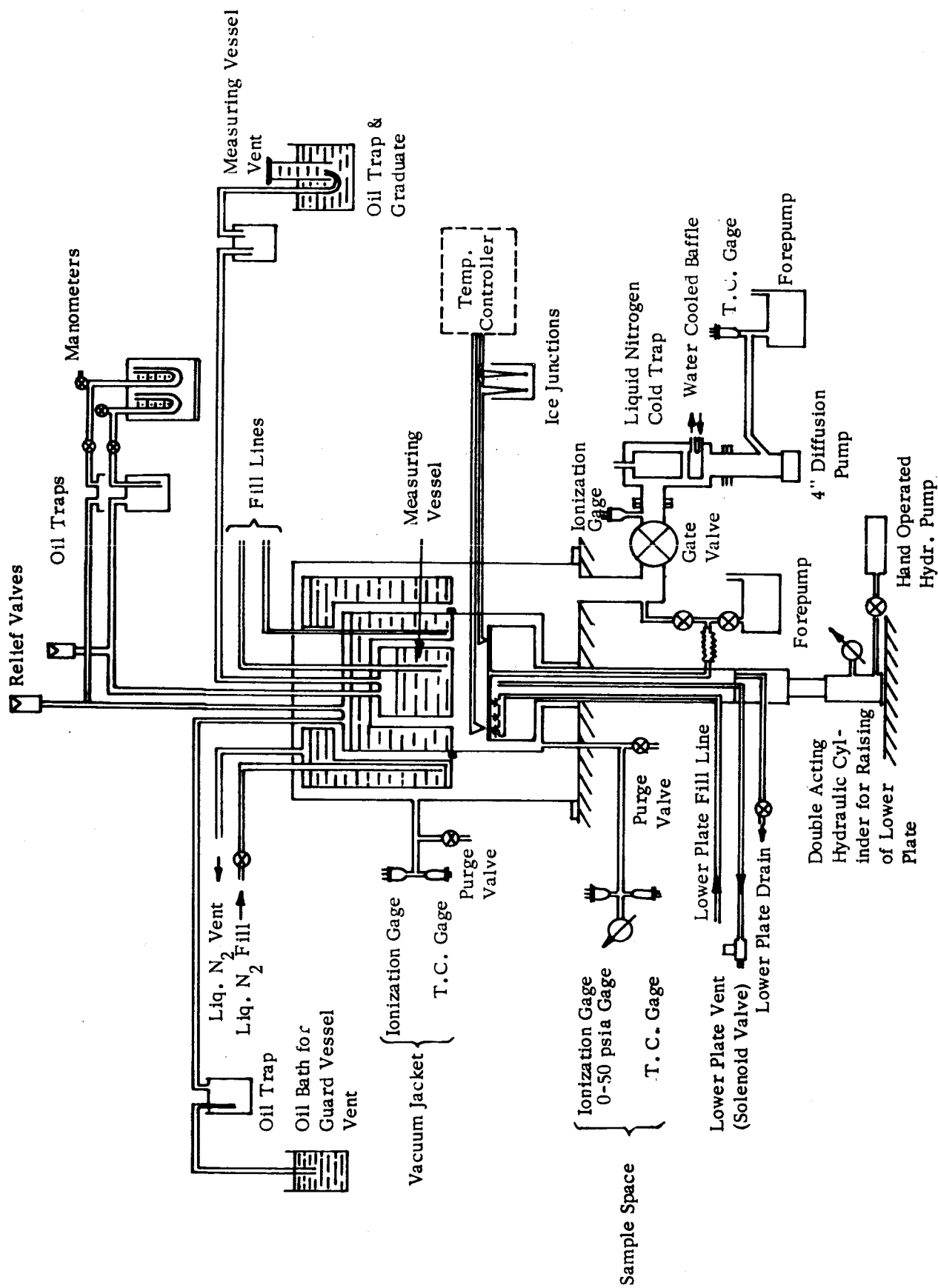


FIGURE IV-B 3 DIAGRAM OF INSTRUMENTATION REQUIRED FOR DOUBLE-GUARDED COLD PLATE THERMAL CONDUCTIVITY APPARATUS

Precautions have to be taken in the operation of the thermal conductivity apparatus so that accurate and reproducible data are obtained. Attention has to be given to the following:

(1) The measuring vessel should not be filled during a test; otherwise, equilibrium conditions tend to be disturbed. For a typical good insulator, the measuring vessel need not be filled for several days. For low-conductivity samples, several hours will elapse before equilibrium can take place.

(2) At very low boil-off rates, stratification of the liquid may occur. To provide better temperature equalization, and thus reduce the probability of stratification occurring, copper wool has been introduced into the measuring vessel.

(3) Close control over the pressure difference in the measuring and guard vessels has to be maintained to prevent stray heat leaks between the two vessels. By controlling the pressure difference to about one millimeter of oil, as measured by manometers connected to both the measuring and the guard vessels, the guard vessel can be arranged to be at a slightly higher temperature than the measuring vessel, thereby preventing boil-off gases from the measuring vessel from condensing on the walls of the guard vessel.

(4) Changes in atmospheric pressure due to weather conditions during a test period are not infrequent and may lead to a corresponding change in the enthalpy of the cryogenic liquid. A correction factor can be applied to the data or a device installed which will compensate for these changes by keeping a constant pressure within the measuring and guard vessels. (See Section IV-C for a description of this device.)

(5) The different heights of cryogenic liquids in the guard vessel and measuring vessel result in a slightly higher temperature in the guard vessel because of the increased head of liquid above the cold plate.

(6) It is essential that the warm and cold plates be kept parallel throughout a test; otherwise, the samples could be subjected to unequal compression resulting in a departure from the postulated one-dimensional heat flow conditions.

(7) It is not desirable to have the diameter of the sample coincide with the diameter of the measuring vessel and then surround it by a guard ring made out of the same sample material. Radiation from the warm plate could be transferred through the small opening between the sample and the guard ring and then be trapped in the clearance space between the measuring and guard vessel, leading to an increase in boil-off rates.

(8) Because the sample is not infinite in extent, the effect of edge losses has to be considered. The design of the sample chamber permits control over the temperature gradient of the surfaces viewed by the sample. In addition, treatment of the sidewalls permits emittance to be controlled so that reradiation or reflection from the warmer parts of the sample chamber can be reduced. Multilayer samples require that exposed edges be protected from radiant heat exchange. Data on edge effects are given in Section IV-D. In some experiments it is advantageous to know how exposed edges of the sample respond to various types of radiative heat inputs which can be provided by the aforementioned techniques.

(9) Although the gas pressures in the bell jar and sample chamber are measured, no direct measurements can be made of the pressure existing within the sample. Thus, some uncertainty exists regarding the contribution of gas conduction to the over-all heat transfer, particularly in those materials which are known to have a finite vapor pressure.

(10) The characterization of the sample with respect to physical properties, such as the emissivity, vapor pressure, and internal structure is essential. Variation in any of these properties can lead to a difference in thermal conductivity between nearly identical samples.

The accuracy of the thermal conductivity apparatus can be established by two techniques: (1) The measuring vessel, guard vessel, and outer guard, as well as the warm plate, are filled with liquid nitrogen. If no stray heat leaks are present, the boil-off rate from the measuring vessel will be zero. (2) The apparatus is calibrated with an accurately measured electrical input to a heater placed in contact with the measuring vessel. In this test all parts of the apparatus are kept at liquid nitrogen temperatures so that the heat evolved by the electrical heater is the only heat source causing the boil-off in the measuring vessel.

Figure IV-B4 shows a typical curve for calibration with the electric heater. The sensitivity of the apparatus is sufficient to permit the measurement of heat flows on the order of 0.1 Btu/hr through the six-inch diameter measuring section. A typical test on multilayer insulations takes 3 - 5 days, depending upon test conditions.

The over-all accuracy of the thermal conductivity apparatus is estimated to be  $\pm 10\%$ . This estimate is based on the accuracy of measuring the volume of boil-off gases, controlling the gas pressures above the cryogenic liquids in the measuring and guard vessels, the effect of atmospheric pressure changes on the boil-off rate, and the temperature measurement of the cold and warm surfaces. The electrical heater calibration tests provided further confirmations of this estimate.

The greatest uncertainty in the test results is associated with the sample itself and the reproducibility of the quality of the sample from one test to the next. Tempered aluminum foil and vinyl-coated glass fiber screen have provided the most reproducible samples. Because the thickness of the vinyl-coated glass fiber screen spacer is not closely controlled, the change in thickness leads also to a change in density of this multilayer insulation.

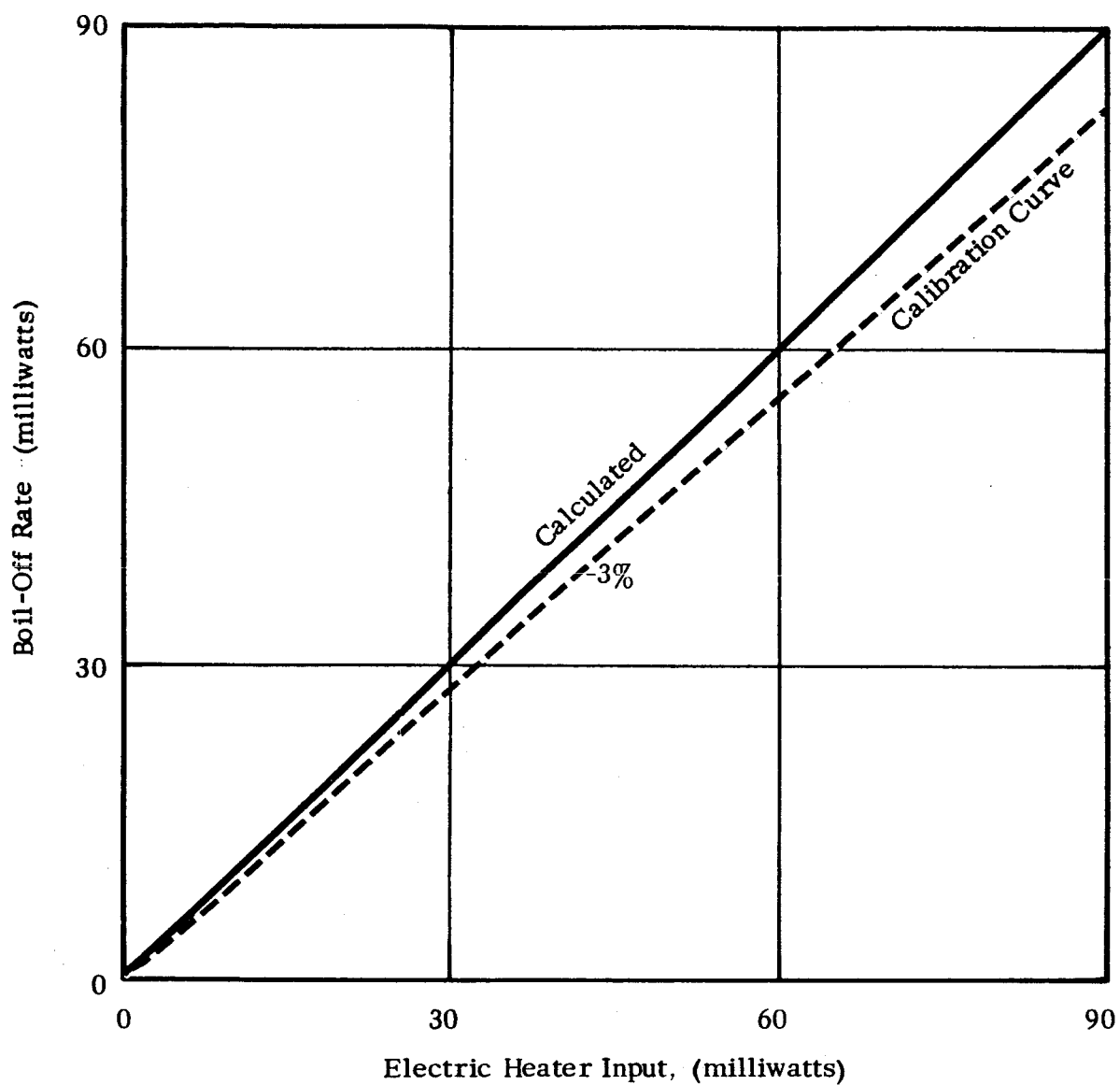


FIGURE IV-B4 RESULTS OF CALIBRATION TESTS OF LIQUID NITROGEN TEMPERATURE ON DOUBLE-GUARDED COLD PLATE APPARATUS

#### IV-C. AUTOMATIC CONTROL DEVICES

The gas pressure over the cryogenic liquid in the measuring vessel and guard vessel is subject to atmospheric pressure changes. These changes can lead directly to boil-off measurement errors. Calculations show that the pressure above the cryogenic liquid should be controlled within  $\pm 0.1$  Torr independent of the atmospheric pressure variation which may extend over several Torr.

Figure IV-C1 shows a diagram of the gas-pressure control system. This device maintains a mercury column at a constant height independent of atmospheric pressure variations. This is achieved by exposing a six-inch diameter surface of mercury to a vacuum and submitting the gas in the measuring vessel and guard vessel to the pressure corresponding to the height of the mercury column. The exit of the line carrying away the boil-off gases is immersed about one inch below the surface of the mercury level in a one-inch diameter tube subjected to atmospheric pressure variations. Changes in the tube mercury level change the height of the mercury column between the level of the mercury surface in the bell jar and the exit of the boil-off gas line. The change in column height is proportional to the ratio of the areas of the tube and the bell jar. Thus, only  $1/36$  of the atmospheric pressure change is sensed by the gas in the measuring and guard vessel. A similar arrangement is used to control the pressure level in the guard vessel. Figure IV-C2 shows the device used for automatic recording of the boil-off rate from the measuring vessel. The boil-off gases are allowed to collect in a graduate closed at the upper end by a solenoid valve. As the pressure builds up, the oil is displaced and collected in a constant level reservoir until the lower photoswitch opens the solenoid and the gases are withdrawn from the graduate with an aspirator. As a result of the pressure reduction, the oil rises in the graduate until the solenoid valve is again closed by the upper photoswitch. At the same time, a pump is actuated which returns the overflow oil into the reservoir. By recording the number of times a fixed volume of gas is collected, the boil-off rate can be obtained.

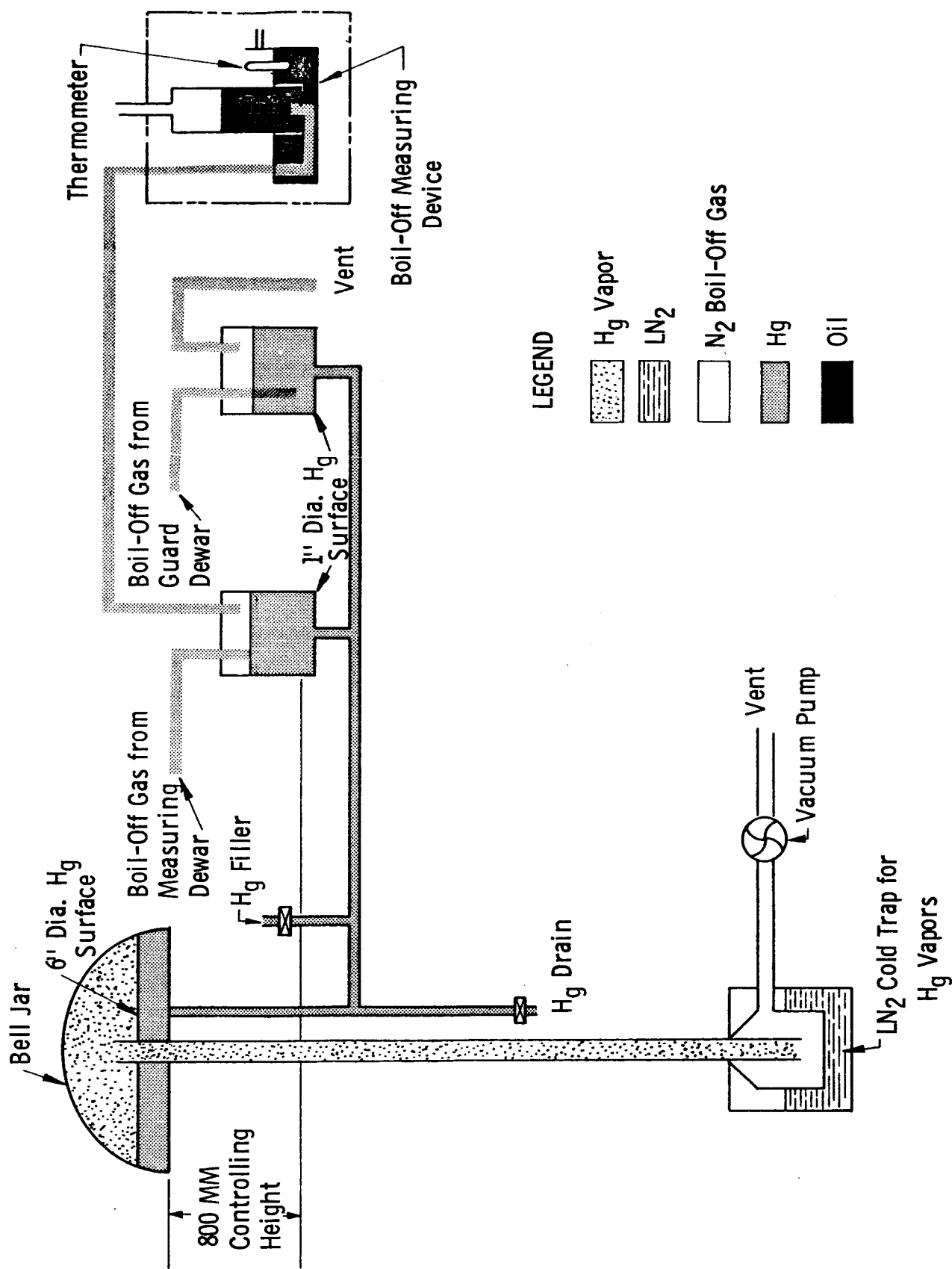


FIGURE IV-C1 GAS-PRESSURE CONTROL SYSTEM

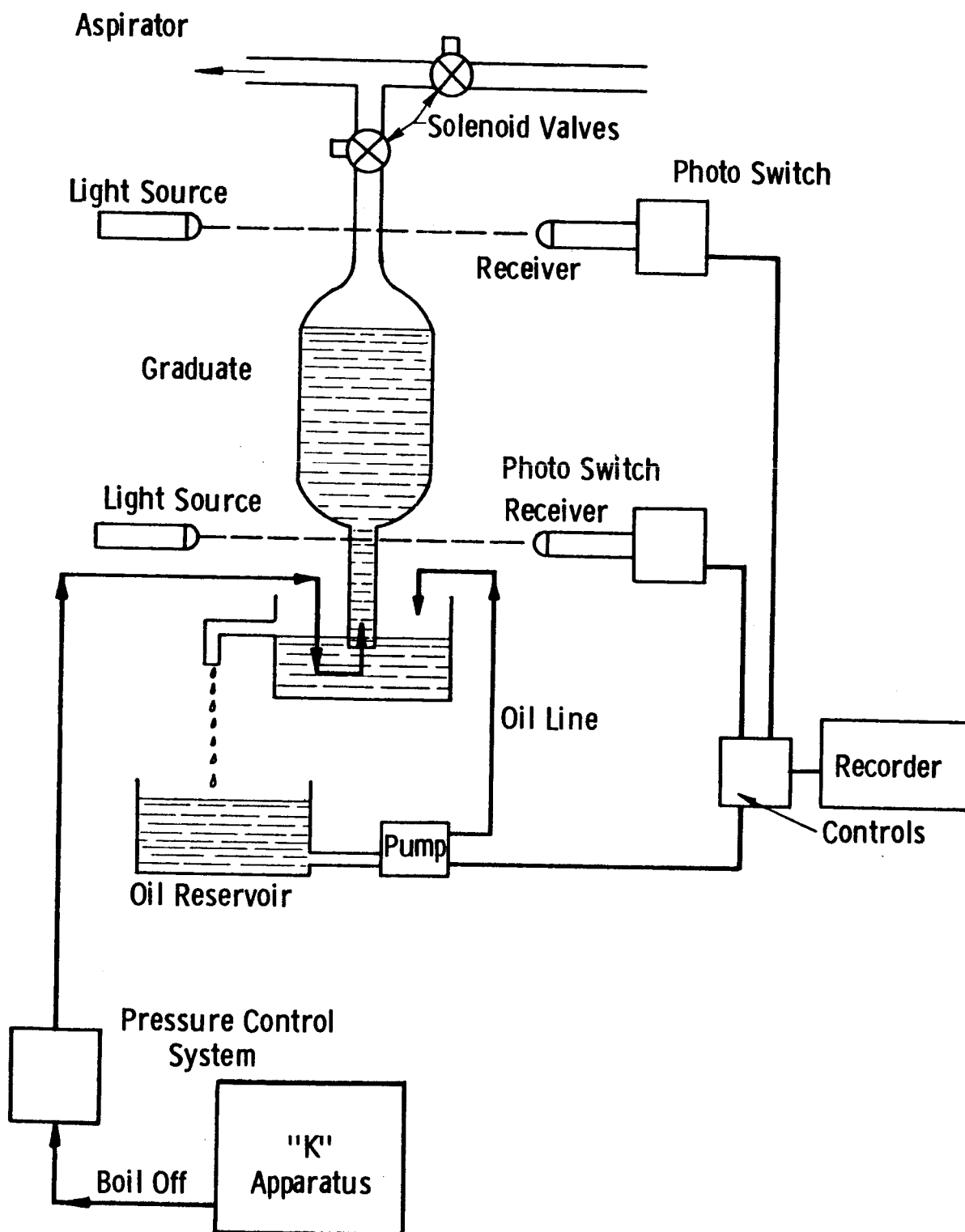


FIGURE IV-C2 AUTOMATIC RECORDING DEVICE FOR BOIL-OFF RATES

#### IV-D. EDGE EFFECTS

The calculations of thermal conductivity of a sample tested in a flat plate apparatus assume one-dimensional heat flow through the portion of the sample below the measuring vessel. Any deviation from this will introduce measurement errors. The guard vessel is designed to minimize deviations from one-dimensional heat flow due to edge effects. Such effects are caused by radiation heat exchange with surfaces of the apparatus at different temperatures than the sample. This results in a distortion of the temperature gradient in the vicinity of the sample edges.

Because of the strongly unisotropic behavior of multilayer insulation, the temperature distortions are rapidly propagated into the sample. In particular, when a certain sample thickness is exceeded, the guarded section of the sample may not be adequate to assure the desired one-dimensional heat flow through the measuring section.

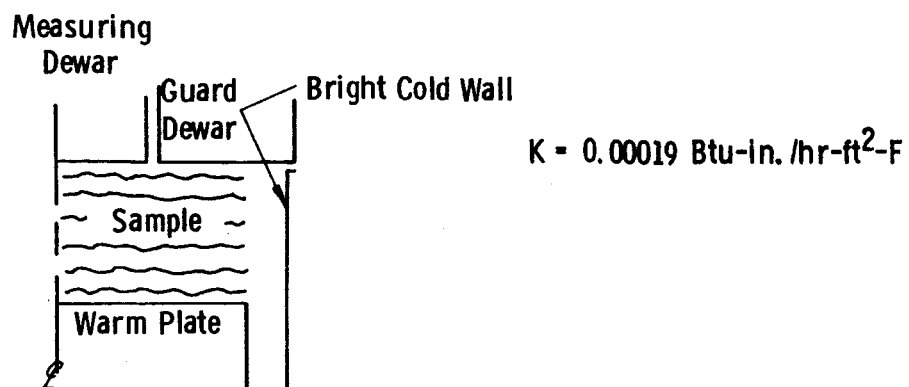
A number of techniques can be used to reduce these edge effects. They rely on control of the temperature of the surfaces seen by the edges, control of the emissivity of the surfaces, and elimination of the radiation emanating from warmer parts of the apparatus. Figure IV-D1 illustrates results of tests on edge effects.

Figure IV-D1a shows a sample consisting of 10 tempered aluminum foils and 11 vinyl-coated glass fiber screen spacers tested without any special precautions taken.

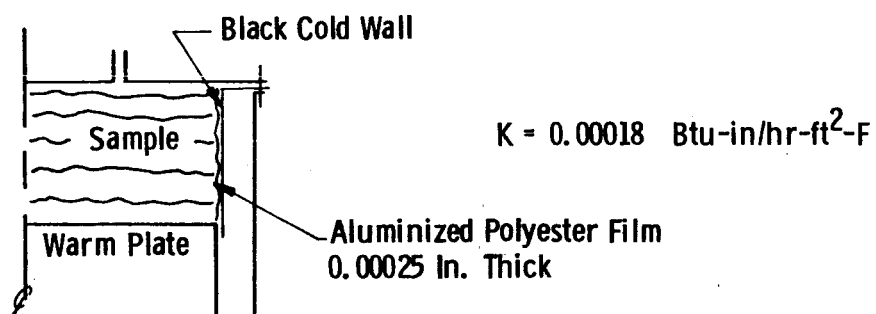
In Figure IV-D1b, a blackened plate in good thermal contact with the guard vessel is placed around the edges, and an aluminized polyester film is wrapped around the sample.

In Figure IV-D1c, the same sample is wrapped with aluminized polyester film. A horizontal copper shield is placed between the warm plate and the sample chamber enclosure, and fastened to the enclosure without touching the warm plate.

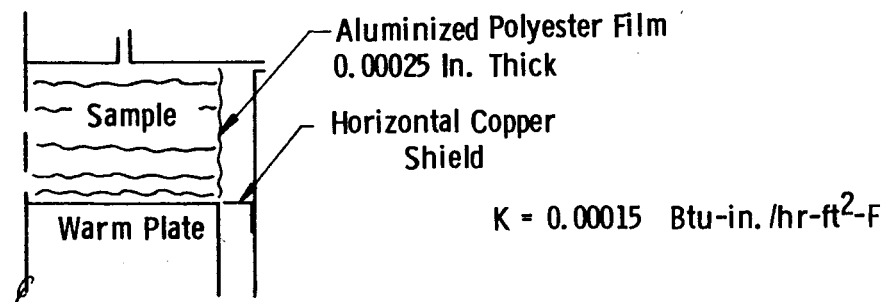
In Figure IV-D1d, only the horizontal copper shield is used. The aluminized polyester film had a tendency to short circuit the aluminum foils which may explain the low result in Test c. The horizontal copper shield appears to be adequate in shielding the sample from the radiation received from the warmer parts of the apparatus and thus promises to reduce the edge effects on multilayer insulation samples.



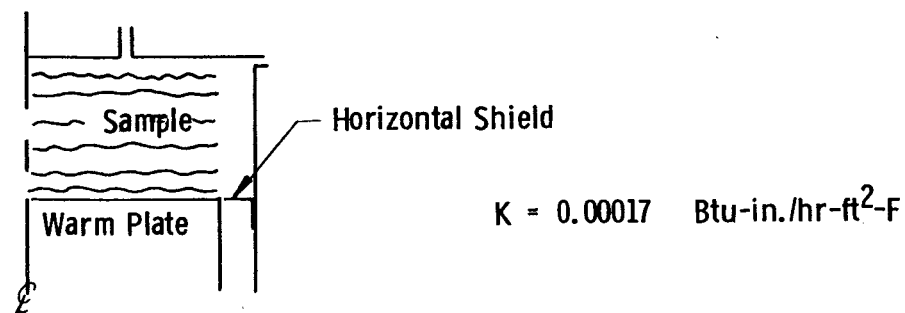
(a)



(b)



(c)



(d)

FIGURE IV-D1 VARIATIONS OF EDGE EFFECTS

## V. EXPERIMENTAL RESULTS

At this time, three double-guarded cold plate apparatus are in use for the measurement of the thermal conductivity of various thermal insulators at liquid hydrogen and liquid nitrogen temperatures. Two units No. 1 and No. 2 are located at the Lewis Research Laboratory in Cleveland, and unit No. 3 is located at the Arthur D. Little Laboratory in Cambridge. The units in Cleveland have been in operation since May and August, 1962, while the unit in Cambridge has been operating since September, 1962. The following data has been obtained on a number of variables affecting thermal conductivity. The data should be considered indicative of the measurements being made. It will be supplemented by additions to this report as new and significant data are obtained.

### V-A. TEMPERATURE

Figure V-A1 shows the influence of temperature on the thermal conductivity of two multilayer insulations at liquid Freon-12, liquid nitrogen and liquid hydrogen boundary conditions. In general, the thermal conductivity obtained at liquid hydrogen temperatures is slightly lower than that obtained at liquid nitrogen temperatures. This decrease in thermal conductivity appears to be due to lower pressures obtained in the sample because of more efficient cryopumping, as well as to a decrease in the solid conduction contribution with temperature. The data show that the temperature dependence of thermal conductivity follows a  $T^3$  law as had been predicted by analysis.

Figure V-A2 shows that the heat flux is primarily a function of the fourth power of the warm plate temperature over the range considered.

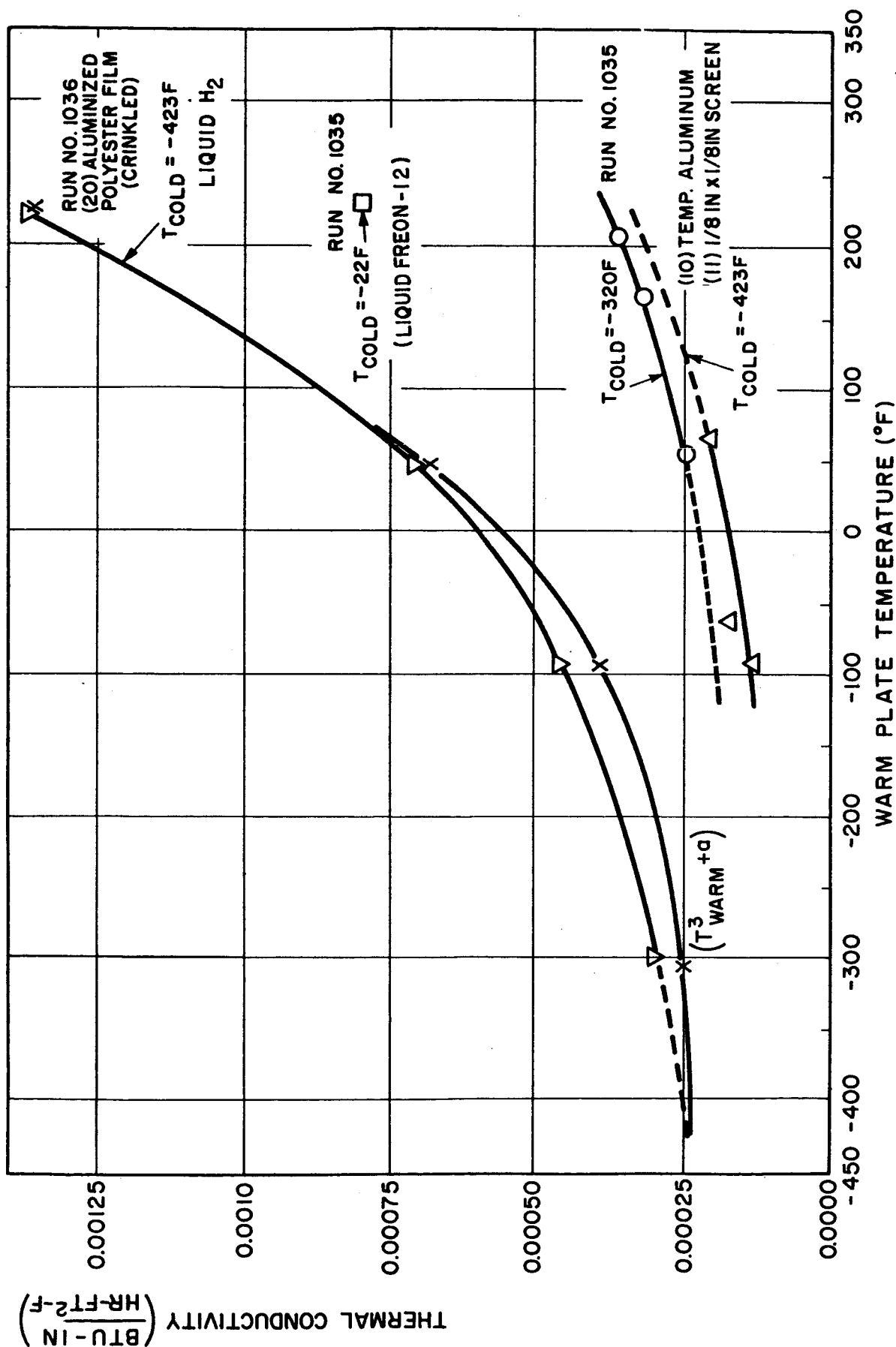


FIGURE V-A1 EFFECT OF BOUNDARY TEMPERATURE ON THERMAL CONDUCTIVITY OF MULTILAYER INSULATIONS

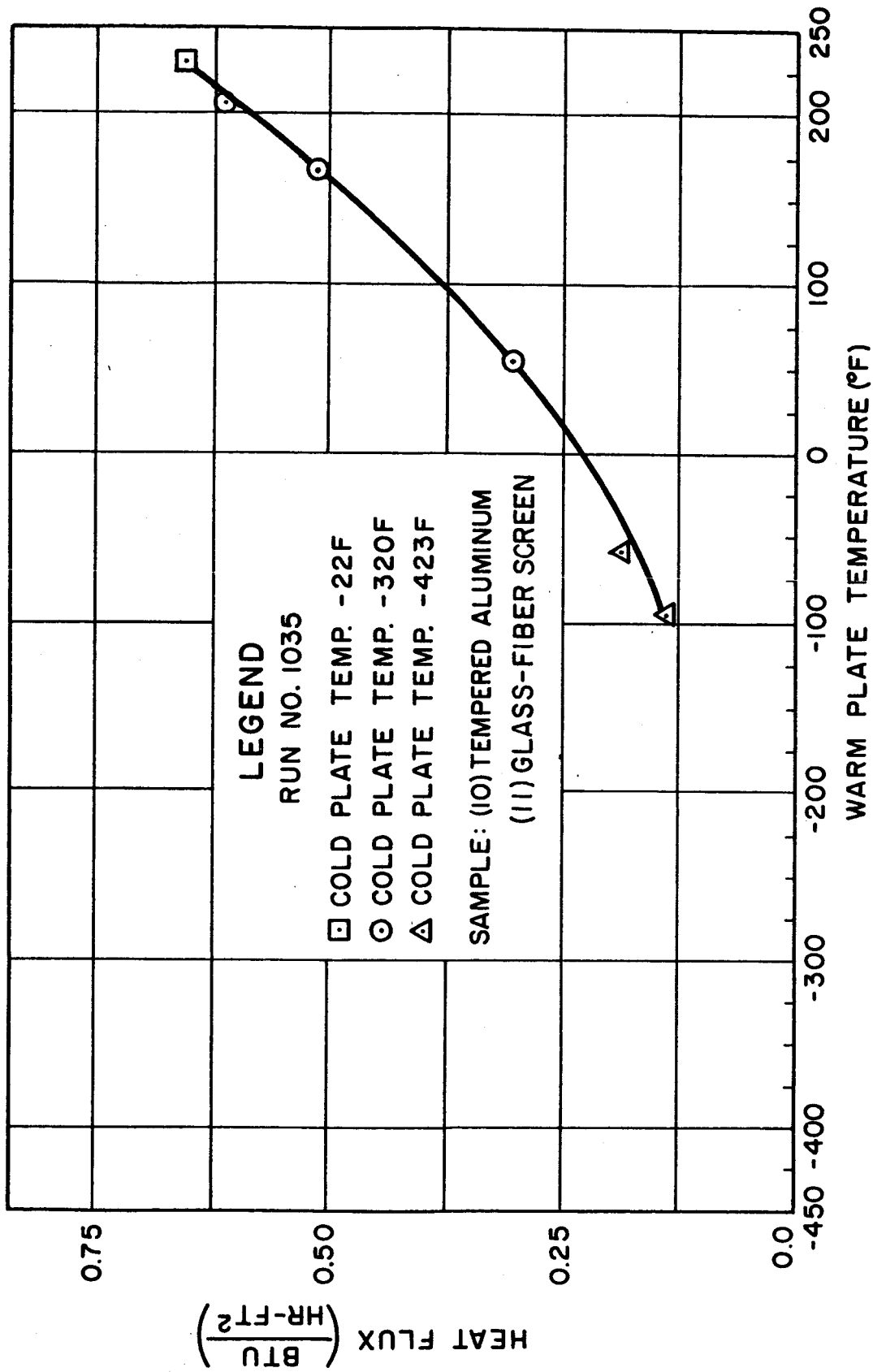


FIGURE V-A2 EFFECT OF WARM PLATE TEMPERATURE ON HEAT FLUX THROUGH MULTILAYER INSULATION

## V-B. DENSITY

The density of a sample tends to influence thermal conductivity. In the case of multilayer insulations, the radiation contribution decreases with increasing number of layers per unit thickness; however, since the solid conduction contribution increases at a greater rate, it is possible to find an optimum number of radiation shields for a specific material combination.<sup>(13)</sup> Figure V-B1 illustrates this behavior.

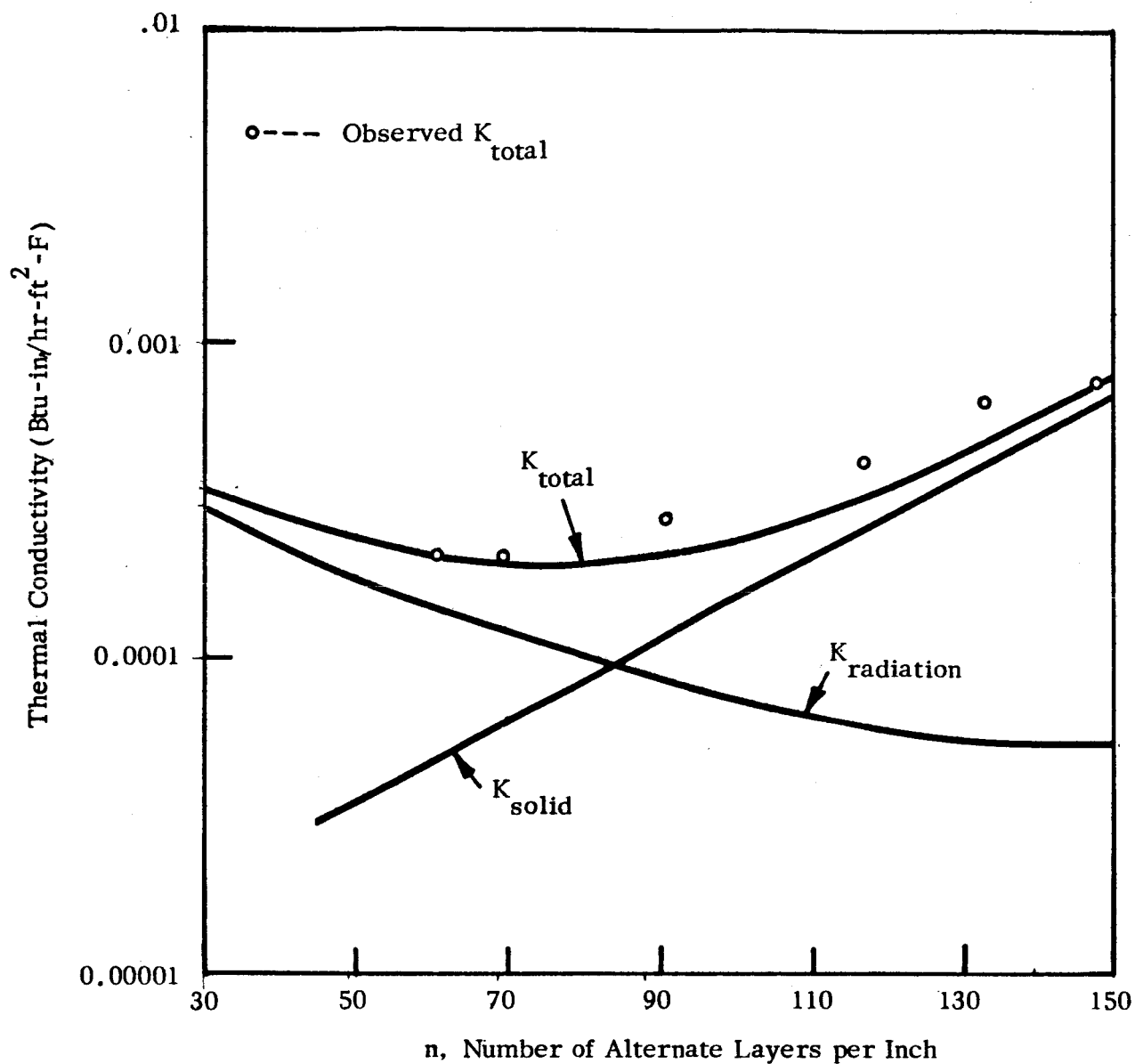


FIGURE V-B1 THE CONTRIBUTION OF SOLID CONDUCTION AND RADIANT HEAT TRANSFER TO THE THERMAL CONDUCTIVITY OF MULTILAYER INSULATIONS

Source: D.I. -J. Wang, "Multiple Layer Insulations"

### V-C. MECHANICAL LOAD

The effect of mechanical load on the density and thereby on the heat flux through a sample of a multilayer insulation is of considerable practical significance. An increase in mechanical load will cause the radiation shields and spacers to be compressed into a thinner sandwich of higher density. A decrease in mechanical load will allow the radiation shield and spacers to return to their original density provided that no permanent deformation has been obtained.

Before the effects of mechanical load on thermal conductivities of multilayer insulation can be obtained, the optimum density has to be established. Three or four thermal conductivity measurements are required to establish this optimum density. In Figure V-C1, the average data for several samples are given to illustrate the following:

(1) With an increase in mechanical load, the solid conduction contribution to heat transfer becomes dominant.

(2) The differences in thermal conductivity at optimum density are the result of differences in the spacer materials. Spacers consisting of fibers have a high contact resistance which impedes solid conduction. With no external load on the insulation, the closeness of the packing of these fibers (and hence the contact resistance) depends upon the previous history such as number of load applications, method of manufacture, and storage conditions.

The crinkled polyester film is subject to a more rapid increase in thermal conductivity under compressive loading compared to other multilayer insulation. The lack of mechanical strength of the thin film leads to a more rapid increase in solid conduction by flattening out crinkles. Multilayer insulations utilizing fiber spacers have comparable thermal conductivities for loads exceeding 3 psi.

(3) After an initial sharp rise in thermal conductivity has been obtained, thermal conductivity is a function of the two-thirds power of the mechanical load. This relationship corresponds to the deformation of a sphere resting on a plane and appears to approximate the deformation of the contact areas between the spacers and the radiation shields. The trend of the effects of mechanical load on thermal conductivity indicates that the insulating effectiveness of most multilayer insulations is greatly reduced under compressive loads.

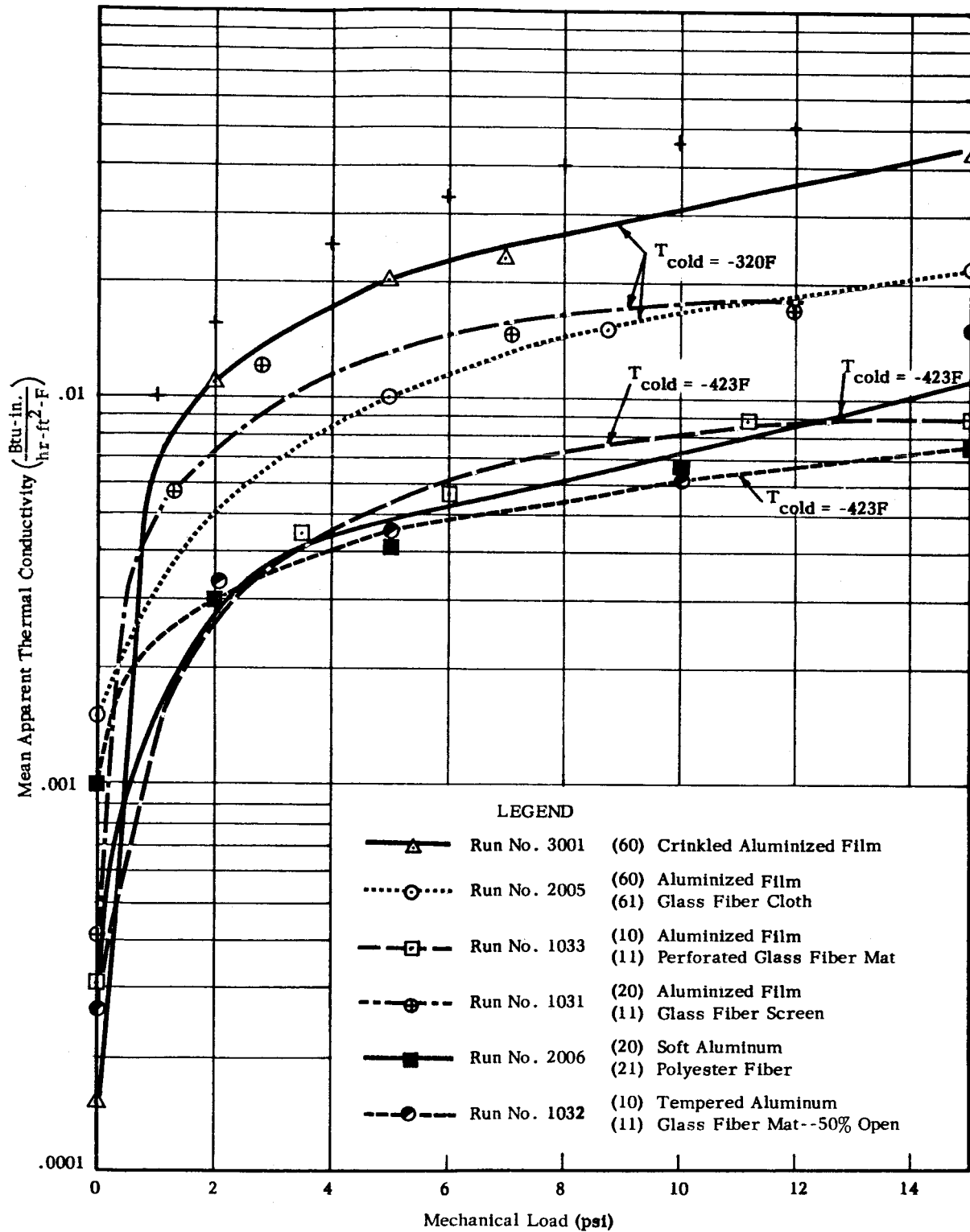


FIGURE V-C1 EFFECT OF MECHANICAL LOADING ON THERMAL CONDUCTIVITY

Figure V-C2 shows the effects of mechanical loads on density for different multilayer insulations. Because a considerable choice exists in the thickness of radiation shields and spacers, the insulation density can be adjusted to meet a particular set of conditions. The selection of a combination of materials may be more influenced by specific design requirements including the effects of lateral heat conduction through the radiation shield, structural integrity, high-temperature stability and production considerations.

The density of the crinkled polyester film is strongly dependent on repeated mechanical load application. Table V-C1 illustrates the results of compression on a sample consisting of 20 shields and indicates the hysteresis effect obtained by repeated compression causing a flattening out of the crinkles. The density of the sample was calculated from the thickness, which was measured during the test in a fixture constructed for this purpose.

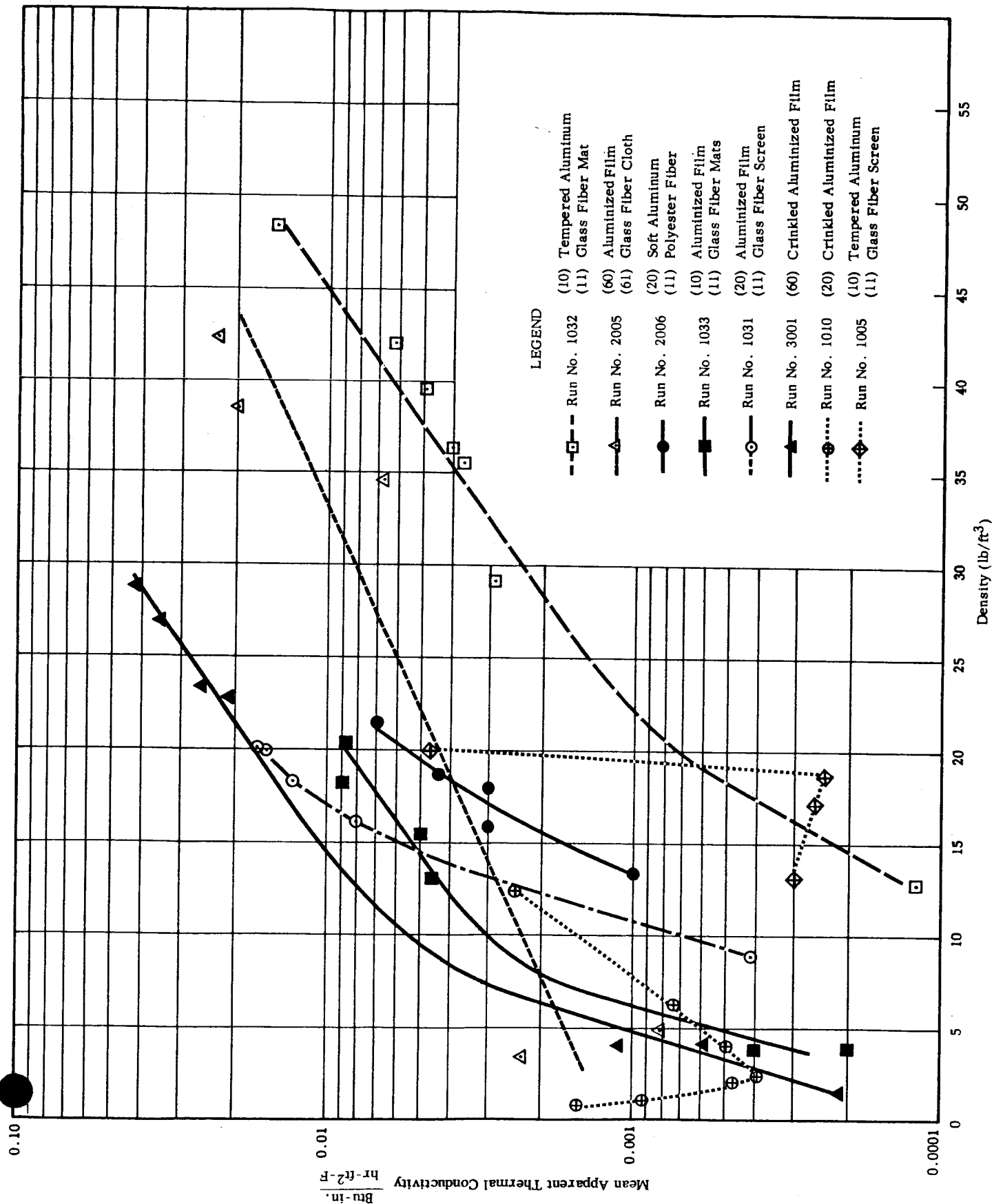


FIGURE V-C2 EFFECT OF DENSITY ON MEAN APPARENT THERMAL CONDUCTIVITY

TABLE V-C1EFFECT OF COMPRESSION ON POLYESTER FILM

	<u>Compressive Load</u> (lb/in. <sup>2</sup> )	<u>Sample Thickness</u> (in. )	<u>Density</u> (lb/ft <sup>2</sup> )
A. 0.00025 inch crinkled polyester film uncompressed	0.000 0.006 0.018 0.054 0.117	1.000 0.500 0.310 0.180 0.125	0.44 0.87 1.39 2.31 3.46
B. Repeat Tests	0.017 0.054 0.164 0.185	0.142 0.080 0.055 0.044	3.05 5.42 7.90 9.87
C. Repeat Tests	0.018 0.054 0.164	0.059 0.051 0.047	7.36 8.50 9.22
D. Repeat Tests	0.185	0.042	10.31

# V-D. CONTACT RESISTANCE

Table V-D1 below shows the results of tests of the influence of contact resistance between a surface and a foam sample. When the space around the sample was evacuated, the contact resistance between the sample and the surface increased to the extent that the heat flux decreased by a factor of four. Since the foam sample had approximately a 90 percent closed cell structure, the conductivity of the bulk of the foam appeared to be unaffected by the evacuation of the gas on the outside. Thus, the increase in the resistance appears to be due to a removal of gas from broken cells near the surface. A similar increase in contact resistance was observed on a second sample of foam when a thin evacuated gap was formed between the cold plate and the sample.

## TABLE V-D1

### THE INFLUENCE OF CONTACT RESISTANCE BETWEEN PLATES AND SAMPLE ON THERMAL CONDUCTIVITY

	Test #	Density $\left(\frac{\text{lb}}{\text{ft}^3}\right)$	Thickness (in)	Heat Flux $\left(\frac{\text{Btu}}{\text{hr} - \text{ft}^2}\right)$	Thermal Conductivity $\left(\frac{\text{Btu} - \text{in}}{\text{hr} - \text{ft}^2 - \text{F}}\right)$	Pressure In Specimen Chamber (Torr)
Polyurethane foam	14c	3.85	0.246	224	0.141	760 (N <sub>2</sub> )*
Polyurethane foam	14b	3.85	0.246	63.8	0.040	10 <sup>-5</sup>
Polyurethane foam	14a	3.85	0.280	23.3	0.0176	10 <sup>-5</sup> (gap)**
Glass fiber re- inforced foam	18b	5.0	0.758	41.2	0.0808	10 <sup>-5</sup>
Glass fiber re- inforced foam	18a	5.0	0.782	22.6	0.0458	10 <sup>-5</sup> (gap)**

\*Nitrogen.

\*\*Evacuated gap.

### V-E. EMISSIVITY

The effect of emissivity on the thermal conductivity of a multilayer sample can be illustrated by tests made on an assembly of aluminized film. In one sample the thermal conductivity was 0.001 Btu-in/hr-ft<sup>2</sup>-F. After a sample was made up from a new shipment from the supplier, a thermal conductivity of 0.0004 Btu-in/hr-ft<sup>2</sup>-F was measured. On checking with the supplier, we learned that the aluminized coating in the sample with the higher thermal conductivity was near the border line of acceptable quality (electrical resistance of 7 ohms/cm<sup>2</sup>).

In another test, aluminum foils in a sample were replaced by foils just received from the supplier. An 80 percent decrease in thermal conductivity was obtained, indicating that either oxidation or a different treatment of the foil had resulted in a reduced emissivity and thereby a lower thermal conductivity. Since the contribution of radiation heat transfer is proportional to the emissivity, considerable quality control is required to assure that reproducible emissivities are obtained.

It is possible that radiation shields placed very close to each other may cause a substantial increase in the radiation heat transfer rate.<sup>(14)</sup> This increase could be caused by the effect of constructive interference when the wave emitted by a foil is reflected back and forth in the small gap between two foils. This can be of importance in the transmission of energy across the gap when the spacing is very small compared to the wavelength of the radiation, as may be occurring at cryogenic temperatures.

## V-F. GAS PRESSURE

The influence of gas pressure on residual gas conduction is of considerable practical importance. Figure V-F1 compares the behavior of a multilayer insulation with powder and fiber insulations as a function of gas pressure. The insulating effectiveness of multilayer insulations tends to decrease rapidly with increased gas pressures, so that at pressures between 10 and 100 microns their thermal conductivity tends to be higher than for an opacified evacuated powder.

This dependence of thermal conductivity on residual gas conduction indicates that every effort has to be made to obtain a low pressure within the multilayer insulation, particularly after reaching space. If the low pressure existing in space is to be relied upon to assist in evacuating the multilayer insulation, steps have to be taken so that the outgassing rate from the insulation surfaces, as well as gas diffusion from the tank due to very small leaks, can be accommodated. Consideration can be given to the geometrical arrangements of the foils which will enhance the pumping of the gas without reducing the effectiveness of the foils as a radiation shield. One such technique is to perforate the foil; however, the perforations have to be small enough so as not to lower the effective emissivity of the foil, since radiation can enter by the same path by which molecules leave.<sup>(15)</sup> Thus, one percent of perforation would cause an increase of emissivity from 0.05 for the undisturbed foil to 0.07, corresponding to a possible 40 percent increase in heat flow.

An analysis of gas conduction through multilayer insulation shows that for a typical assembly of 100 foils, the allowable diffusion rate from the liquid hydrogen fuel tank is about one pound of hydrogen per year for each 1000 sq ft of tank surface assuming 1% perforation. This would correspond to a maximum pressure of about  $10^{-4}$  Torr within the insulated space when exposed to space vacuum. This pressure would not tend to lower the insulating effectiveness appreciably. However, this diffusion rate on the ground could not be easily removed by a vacuum pump connected to an insulation system and could lead to a pressure rise of undesirable proportions. Therefore, more stringent criteria for diffusion rates would have to be used to assure that pressure would not rise above a maximum value consistent with desired insulating effectiveness.

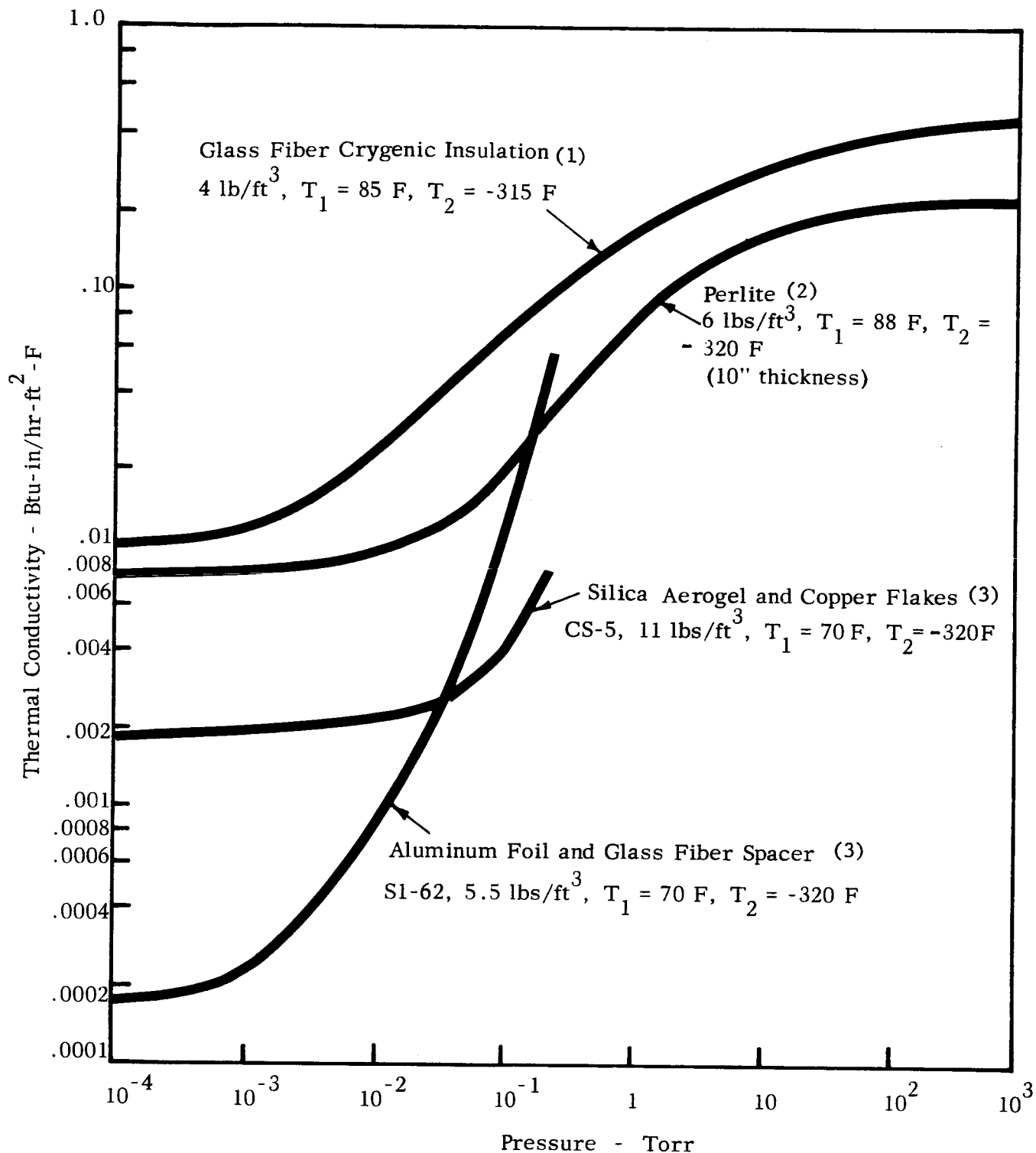


FIGURE V-F1 THE DEPENDENCE OF THERMAL CONDUCTIVITY ON GAS PRESSURE OF TYPICAL POWDERS, FIBERS, AND MULTILAYER INSULATIONS

- Source: (1) R.M. Christiansen, M. Hollingsworth, Jr., and H.N. Marsh, Jr., "Low Temperature Insulating Systems", Adv. in Cryogenic Engineering, K.D. Timmerhaus (ed.) Vol. 5, Plenum Press, Inc. (New York 1960) p. 171
- (2) D.B. Chelton and D.B. Mann, Cryogenic Data Book
- (3) M.A. Dubs and L.I. Dana, "Superinsulation for the Large Scale Storage and Transport of Liquefied Gases", Annexe 1961-5, P. 75, Bull. Inst. Ont. du Froid, Paris

## VI. REQUIREMENTS FOR APPLICATION OF MULTILAYER INSULATION TO LIQUID HYDROGEN TANKS

After examining the data on thermal conductivity of multilayer insulations, it is not surprising that the impression is gained that an adequate solution is near at hand for overcoming the insulation problems of large liquid hydrogen tanks for space vehicles. We can conclude from available data that multilayer insulations of quite reasonable thickness will be adequate to reduce the boil-off losses to acceptable proportions. In fact, only insulation systems of such high effectiveness are capable of meeting the objectives of long-term space missions. However, multilayer insulations have been successfully applied only to ground-based, double-walled storage vessels, and no large insulated cryogenic tanks have yet undergone the rigors of space flight.

In the following discussion, typical design parameters influencing selection of insulations are given and conceptual designs are briefly pointed out to illustrate approaches which have been presented in the literature. Supporting systems and insulation penetrations discussed herein are based on initial theoretical considerations only. Results of work now in progress under this contract and information to be obtained from other sources will be presented in subsequent additions to this chapter.

### VI-A. DESIGN PARAMETERS

Prior to the selection of a suitable insulation system, several design parameters have to be established:

#### 1. Heat Balance for Liquid Propellant Storage Systems

The heat balance will be influenced by:<sup>(16)</sup>

a. The radiative heat input from the sun and other solar system bodies. This input will depend upon the degree of orientation of the vehicle. In many cases, controlled orientation can materially simplify the thermal insulation problem.

b. Radiative heat inputs from other portions of the vehicle. These inputs can be minimized by judicious placement of liquid-oxygen tanks to shield liquid-hydrogen tanks from the engine.

c. Conductive heat inputs through pipes and supports. If the insulating effectiveness of the multilayer insulation is not to be offset, these heat inputs must remain a small percentage of the over-all heat flow into the tank.

d. Radiative heat losses to space. The outside surface coating should accept as little radiation as possible while radiating strongly to the surroundings.

## 2. Methods Used For The Storage Of Liquid Propellants

Three principal methods can be identified. Liquid propellants can be stored in:

- a. A vented tank,
- b. A nonvented tank with a variable pressure, or
- c. A refrigerated tank in combination with the above.

The specific method chosen will have an influence on the thermal stratification and condition of the liquid hydrogen during both ground standby and space flight. The approach selected may also influence the tank shape, e.g., in a nonvented, variable-pressure tank, an increase in pressure may lead to a change in the shape of the vessel. Analysis has shown<sup>(1)</sup> that a definite advantage exists in supplying refrigeration for a number of mission profiles of interest, because it eliminates boil-off losses and reduces the thickness of insulation required. (See Figure III-A1.)

## 3. Meteoroid Protections

Based on our present understanding of the hazards to large liquid propellant tanks by meteoroid impact, it appears that an effective meteoroid protection system has to be provided as a means of assuring the survival of the tank in space during extended missions. This protection system, which might consist of a thin bumper erected after the vehicle has left the earth's atmosphere, could perform an additional thermal protection function by having its surfaces coated so as to minimize radiant heating by outside sources.

## 4. Production Consideration

Large liquid hydrogen tanks will undergo a number of certification tests, static firing tests, and inspection tests, all involving transportation and handling by a variety of means before erection at the launch site. These conditions impose practical limits on the type of thermal protection systems selected, from the point of view of sensitivity to damage, ease of repair, maintenance under field conditions, and compatibility with inspection procedures.

Among these inspection procedures, leak detection of the complete tank structure at various points of tests and at the launch site is of great importance. The thermal protection system has to be compatible with procedures for leak detection, as any undetected leakage into the protection system can nullify its insulating effectiveness under space conditions or even create explosion hazards.

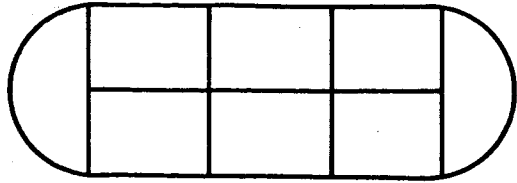
## VI-B. METHODS OF INSTALLATION

Once a heat transfer analysis and an optimization procedure have been carried out; the thermal insulation system has been characterized as to the number and type of foils, the type of spacers, and the over-all density requirement; and the thermal conductivity of selected thermal insulation systems has been measured the installation techniques can be investigated. The merits of internal versus external insulation with respect to the tank design have to be considered. Foam insulation may be used in both approaches while multilayer insulation cannot be used internally to the tank unless more reliable vacuum sealing materials for this purpose are developed.

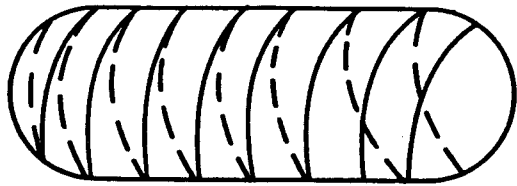
The installation technique to be used with multilayer insulations will depend on the specific tank shape, i.e., cylinder, sphere, ellipsoid, or torroid. Several precautions will have to be taken so as not to decrease the over-all insulating effectiveness of the system: (1) gaps between radiation shields have to be minimized to prevent increased radiation heat transfer, (2) the tension of the individual foils or spacers while wrapping around the tank has to be carefully adjusted, to prevent subjecting the insulation layers to mechanical loads during the application or subsequent dimensional changes of the tank, (3) the wrapping method has to avoid repeated overlaps of sheet edges, in particular where gore sections meet, and seams in alternate layers should be staggered to prevent doubling of the insulation thickness in specific areas.

Figure VI-B1 shows typical installation techniques:

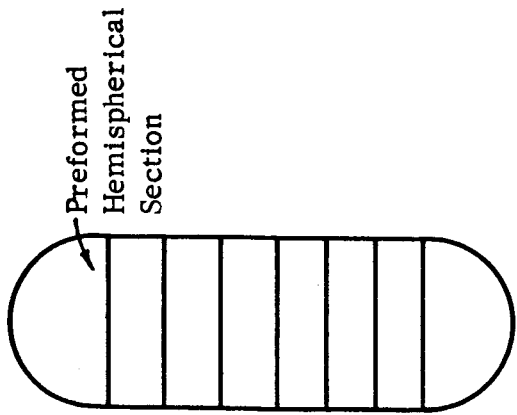
- (1) Straight-Wrap--Layers of insulation are wrapped around the straight tank walls in bands, using as wide a material as practical. The edges of subsequent layers are staggered to cover joints between individual bands. With large tanks, the hemispherical ends are covered by staggered gore sections preformed to the desired curvature; for smaller tanks, the ends are made up of preformed hemispherical layers.
- (2) Spiral Wrap--Alternate layers of materials are spirally wound around a straight cylindrical section with each succeeding layer crossing the underlying layers at an angle. This technique is applicable to smaller diameter pipes and can be used to insulate T-joints and curved pipes.



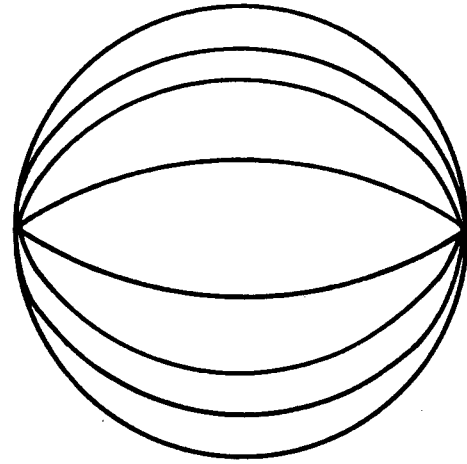
Tile Assembly



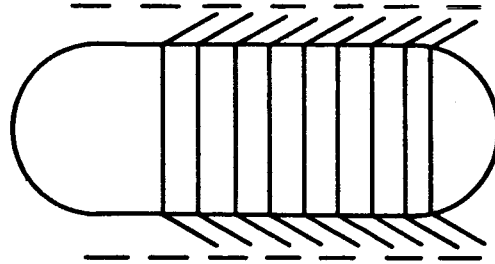
Spiral Wrap



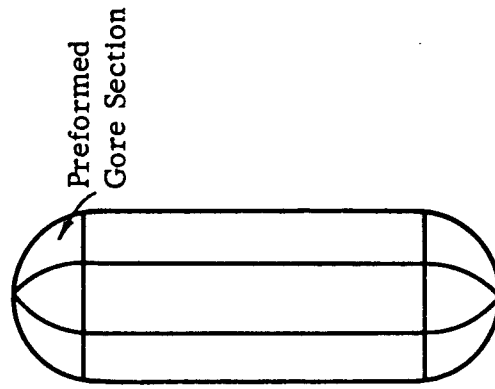
Straight Wrap



Gore Section Wrap



Skirt Wrap



Longitudinal Sections

FIGURE VI-B1 TECHNIQUES FOR INSTALLING MULTILAYER INSULATION ON A TANK

- (3) Tile Assembly--Several layers of multilayer insulation are preassembled and attached to the cylindrical section of the tank wall. Subsequent layers are arranged to cover the joints of the lower layers. The thickness of the preassembled layers has to be chosen to prevent significant radiant heat leaks through the gaps formed by the layers.
- (4) Longitudinal Section--Several layers of insulation are preassembled and placed longitudinally on the cylindrical section of the tank. Alternate layers are staggered to cover joints. This technique may be suitable for large tanks where wrapping would be difficult to accomplish.
- (5) Skirt Wrap--This technique is similar in concept to the straight wrap except that individual layers are fastened on the upper circumferential edge just above the preceding layer and overlapping the layer below over most of its length. This technique can be used with plastic films possessing very little mechanical strength if an outer plastic skin is applied over the completed assembly.
- (6) Gore Section Wrap--Hemispherical ends of cylindrical tanks or spherical tanks require that layers be applied in sections conforming to the curved geometry. This can be achieved by using either preformed gore sections or hemispherical sections concentric with the tank ends. Preforming may not be essential if plastic films are used which conform easily to the curvature without introducing objectionable folds. Projections of the surface may be used to obtain the curvature without folding.

Considerable care has to be taken in designing the shape and form of the individual layers. Approaches which have already been used in the aircraft industry in the designing and shaping of wing and fuselage coverings should be applicable. The attachment of the insulation layers using bands, pins or adhesives has to be accomplished without a substantial decrease in insulating effectiveness.

More detailed information about the above techniques will be presented in supplements to this report.

The particular method of application may be further influenced by the following considerations:

(1) The insulation, when applied to a warm tank, will have to accommodate thermal contraction when the tank is filled, and, conversely, in a tank used for nonvented storage, insulation will have to accommodate expansion due to an increase in gas pressure. In a sense, the insulation has to be capable of breathing with the tank without opening up joints and seams or suffering deterioration.

(2) Ground standby conditions may require that the insulated space be ventilated with a noncondensing purging gas, e.g., helium to prevent condensation of air and other vapors. Provisions have to be made allowing this gas to escape from within the insulation as the vehicle leaves the earth's atmosphere. Two conditions have to be met: (a) the gas has to escape at a sufficient velocity but without causing pressure differentials which could lead to rupture of the foil insulation and (b) the thermal conductivity of the multifoil insulation must be reduced to the desirable low values in the shortest possible time by using the external space vacuum for pumping.

(3) The temperatures generated by aerodynamic heating on the outside of the insulation system require that suitable materials be employed as a means of forestalling a serious deterioration in the desirable emissive properties of the outside coatings or a marked deterioration in the strength of the outside layers of the insulation making them incapable of withstanding aerodynamic forces. Thus, it is necessary to select and to install materials with desirable strength characteristics and physical properties for the specific temperature range.

### VI-C. CONDUCTIVE HEAT LEAKS AT DISCONTINUITIES DUE TO JOINTS, SUPPORTS, AND PIPING ATTACHMENTS

Once the basic requirements for the payload and the weight of the cryogenic propellants to complete specific missions are known, the insulating effectiveness of the thermal protection system and the maximum allowable heat leak through discontinuities caused by joints, supports, and piping attachments can be specified. As a rough design guide, no more than 30 percent of the total heat leak into the tank should be caused by such discontinuities. Heat leaks that are higher would tend to nullify the effectiveness of the insulation and might not warrant the application of multilayer insulation.

Analyses have been carried out on the heat leaks due to insulation penetrations and discontinuities.<sup>(17)</sup> These can be classified as:

(a) Weak thermal shorts where a linearized radiation boundary condition can be applied with an acceptable accuracy, e.g., where the surface temperature is within 10% of the adiabatic wall temperature.

(b) Strong thermal shorts when the depression of the temperature at the outer surface of a foil exceeds 10% of the adiabatic wall temperature and when the analytical solution of the problem is complicated by a nonlinear boundary condition.

(c) Absolute thermal shorts where the penetration is so highly conductive that the tank wall and the outside surface of the short are nearly at the same temperature.

Conductive heat leaks are of particular concern after the space vehicle has left the earth's atmosphere and is subject to the various radiative heat inputs from the sun and other solar system bodies.

#### 1. Weak Thermal Shorts

Multilayer insulations can be used with materials such as Teflon to meet structural requirements and to satisfy the weak thermal short condition. Steel or other separators would not fall into the category of weak thermal shorts unless insulator could be installed between the multilayers and the penetration. In the case of aluminized film, weak thermal shorts could be obtained for reasonable thicknesses of very poor conducting structural materials when the thickness of the film assembly is greater than one inch. Figure VI-C1 shows the maximum widths of various materials penetrating multilayer insulations when the weak thermal short approximation is applicable.

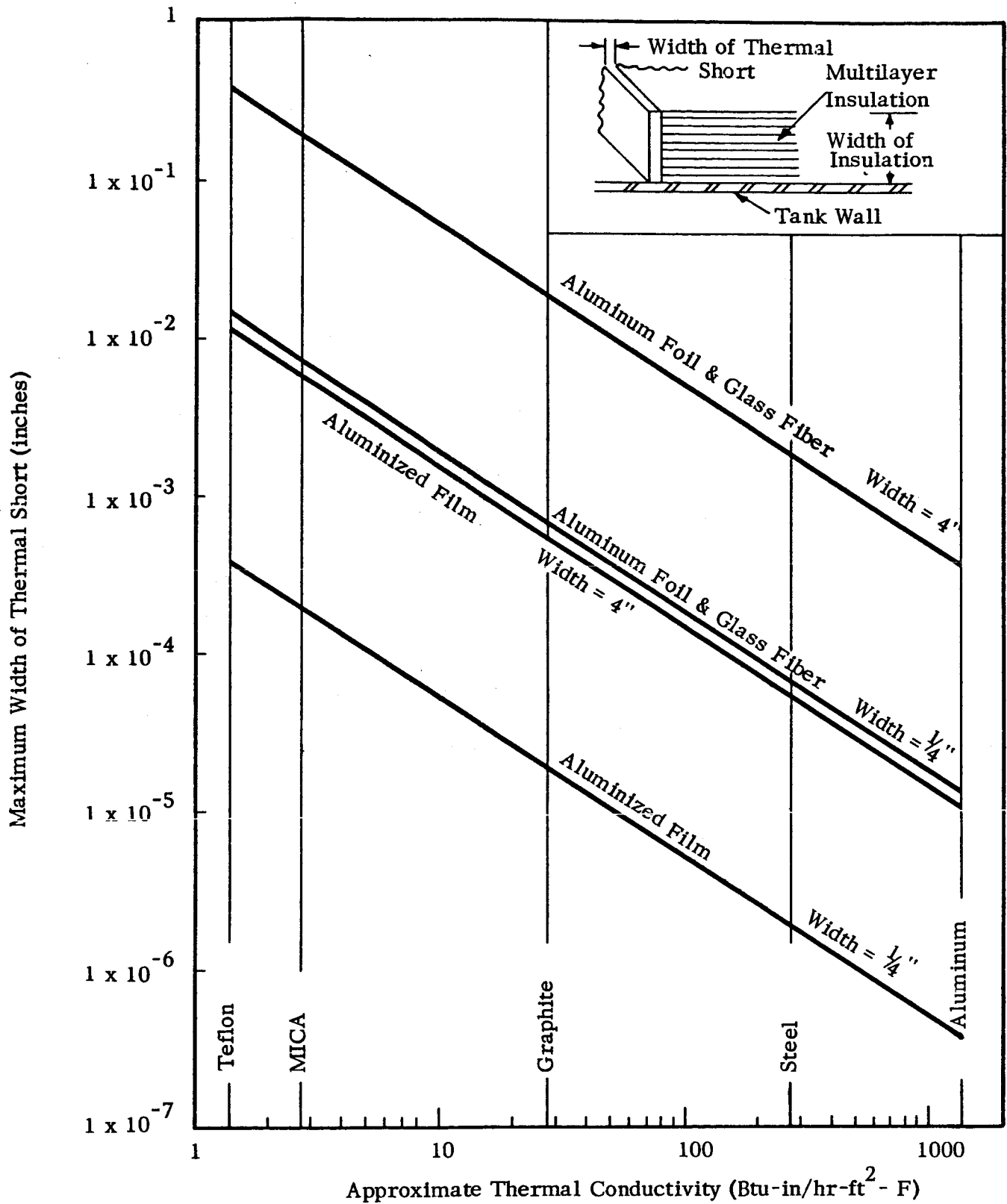


FIGURE VI-C1

THE MAXIMUM WIDTH OF VARIOUS THERMAL SHORT MATERIALS PENETRATING MULTILAYER INSULATIONS

The design of the thermal protection system, even with weak thermal shorts, may have to be modified so that the over-all heat leak is within permissible limits. To illustrate this point, a cylindrical tank 10 feet in diameter and 20 feet long will contain about five thousand pounds of liquid hydrogen and its cylindrical surface area would be 628 sq ft. If there are two 10-mil plastic dividing strips around this tank, then it can be shown that the heat leak through these strips would be equivalent to that of 520 sq ft of insulation. Therefore, the over-all heat leak would be increased by more than 80 percent.

## 2. Strong Thermal Shorts

Because heat leaks associated with strong thermal shorts are greater than would occur from weak thermal shorts, design approaches have to be used to convert strong shorts to weak thermal shorts.

The approach in reducing the heat leak due to a strong thermal short is to separate them from the ends of the multilayer insulation, thus bringing them into the range of weak thermal shorts. Examples of the approach that can be followed to decrease the effect of a strong thermal short are shown in Figure VI-C2. This figure shows the following:

- (a) A strip of evacuated insulation (fibers or foam) separating multilayer insulation from a thermal short.
- (b) A square section of evacuated insulation placed in a corner to protect the foils in one direction from being shorted by those in the other direction when the radiant flux impinges equally on both surfaces of the insulation.
- (c) A square section of evacuated insulation, the upper side of which is kept adiabatic to protect a joint between a tank wall and a large pipe or a structural support with negligible heat flow from the warm end to which these elements would be connected.
- (d) A square section of evacuated insulation provided with a protective radiation shield, the upper side of which receives the same radiant flux as does the multilayer insulation.

Calculations have shown that for a surface temperature of 300°K and a liquid temperature of 20°K, the heat leak due to the presence of a one-foot length of a square cross section of evacuated insulation is equivalent to from 0.5 to 1.5 sq ft of undisturbed multilayer insulation. The dimensions of the square cross section do not influence this result for insulation thicknesses in the order of one inch.

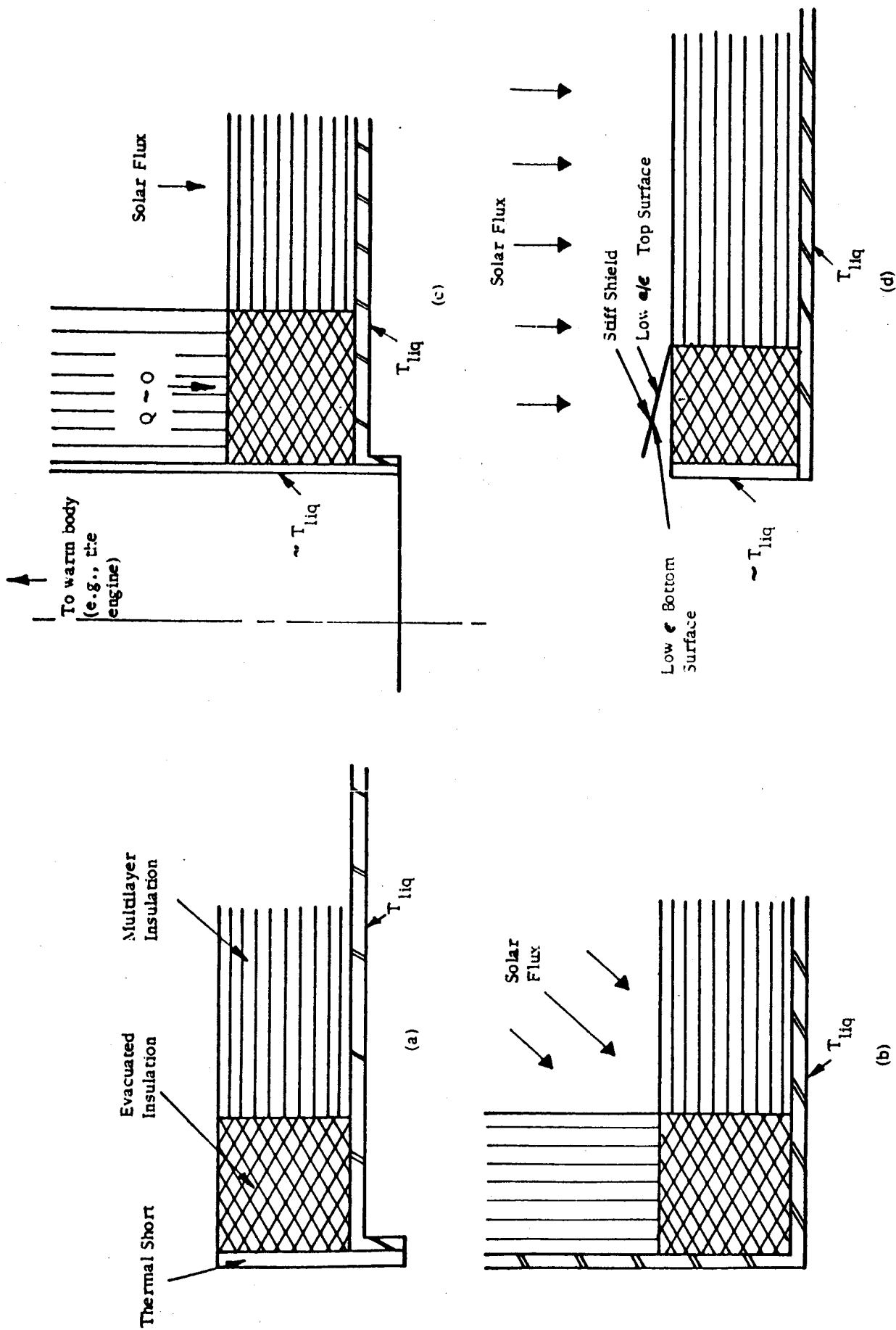


FIGURE VI-C2 TECHNIQUES FOR DECREASING THE EFFECT OF THERMAL SHORTS

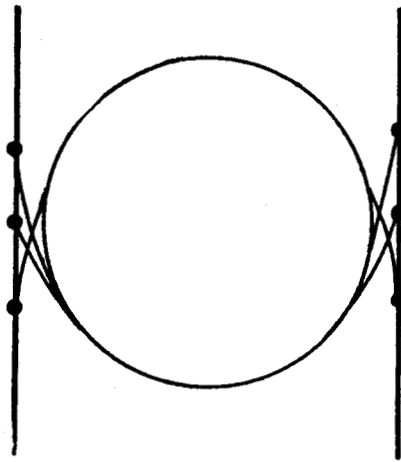
Splices and terminating insulation sections should be placed on the shady side of the tank or be protected by a shadow shield to reduce the possibility of edge effects at discontinuities.

Based on these considerations it can be seen that joints, supports, and piping attachments have to be given considerable attention, and special design techniques have to be employed so that the heat leak can be kept to acceptable proportions.

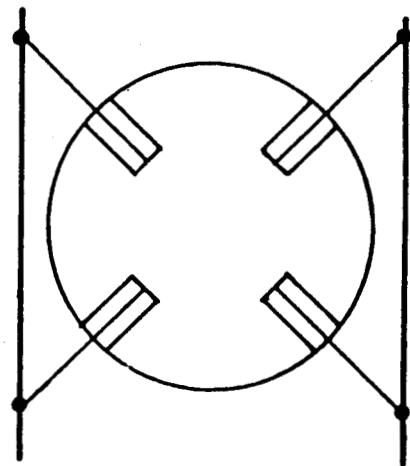
### 3. Methods of Tank Support

When the hydrogen tank is to be placed inside a shroud, the support methods shown in Figure VI-C3 can be employed. The supports are arranged in such a manner that loads in several axial directions can be accommodated. The external cradle support requires that the insulation be under a compressive load during acceleration of the vehicle. However, a system of springs can be arranged to lift this compressive load once zero gravity conditions have been achieved. Pin-jointed bar supports or pretensioned cables can be anchored outside the tanks with connection to re-entrant pipes.

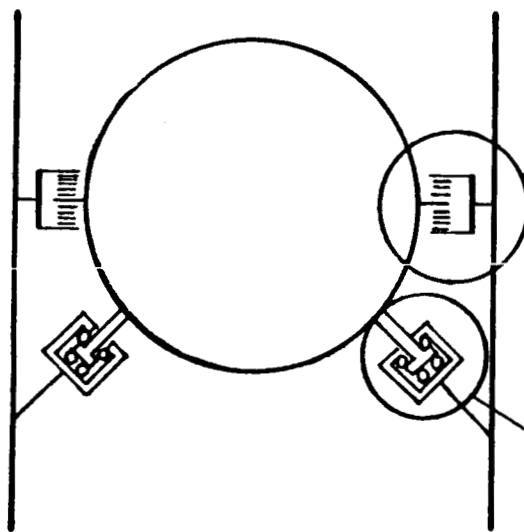
Stainless steel washers dusted with insulating powders have been found to give excellent performance in the support of heavy loads.<sup>(18)</sup> Such washers are primarily designed to withstand axial loads, although they can be formed to take limited radial loads. (See Figure VI-C3.) Passing tension members through the washers can provide additional structural rigidity. A limited amount of work has been done in using ceramic bearings to take radial and axial thrust. The object here is to minimize the heat flow across the contact area between the ball and the bearing surface by minimizing thermal conductivity and maximizing the modulus of elasticity to reduce the area of contact.



External Cradle Support



Internal Rod Support



Multiple Thermal  
Resistance Supports

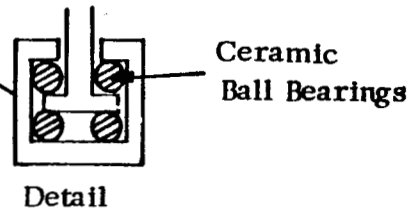
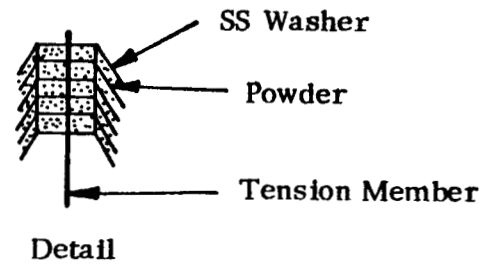


FIGURE VI-C3 TECHNIQUES FOR SUPPORTING TANKS WITHIN A SHROUD

## VI-D. LAUNCH ENVIRONMENTAL INFLUENCES

Although the design of the thermal protection system is primarily directed towards meeting the space-flight portion of the mission, the design will be greatly influenced by the preflight, ground-standby and boost-phase portions of the mission. Because these phases may control the practical application problems, it is of interest to consider them in detail.

### 1. Preflight

The insulating effectiveness of multilayer insulation will be influenced by the environment encountered by the insulating materials during the production, transportation and preflight check out procedures. A specific requirement will be to assure the cleanliness during all phases of preflight procedures so as to prevent an increase in the emissivity of radiation shields through fingerprints caused by inadvertent handling, exposure to corrosive or humid atmospheres, and damage during transport. The out-gassing of the foil and spacer materials can only be reduced to manageable proportions by assuring that the tank walls themselves have been adequately out-gassed prior to installing the insulation and that all materials are dry and are kept in a dry atmosphere after they have been applied. Any deviation from cleanliness requirements will lead to an increase in the out-gassing rate. This increase will lengthen the evacuation time of the multilayer insulation even after the vehicle has reached operating altitudes and will reduce the over-all insulating effectiveness.

### 2. Ground Standby

To allow for the delay time which can be expected while the fueled vehicle is kept on the launch pad, insulation has to be adequate to reduce the magnitude of boil-off losses and prevent condensation or freezing of gases on the tank walls. The following approaches can be used to achieve this:

(a) An outside jacket is provided, which permits the insulation to be evacuated on the ground by cryopumping after the insulation has been flushed with an easily condensable gas such as  $\text{CO}_2$  to exclude residual hydrogen in the air. Because the weight of a rigid shell capable of withstanding atmospheric loads would be prohibitive, a light-weight jacket which encloses the insulation can be considered. (See Figure VI-D1a, Detail A.) This jacket can be designed to be completely flexible and gas tight. It would be used in conjunction with a tank enclosed by a shroud capable of withstanding aerodynamic forces. In this case the insulation is compressed by atmospheric pressure, which disappears when high altitudes are reached. The compressed insulation, although suffering a considerable deterioration in insulating effectiveness (see Figure V-C1), would reduce the boil-off losses to manageable proportions. A layer

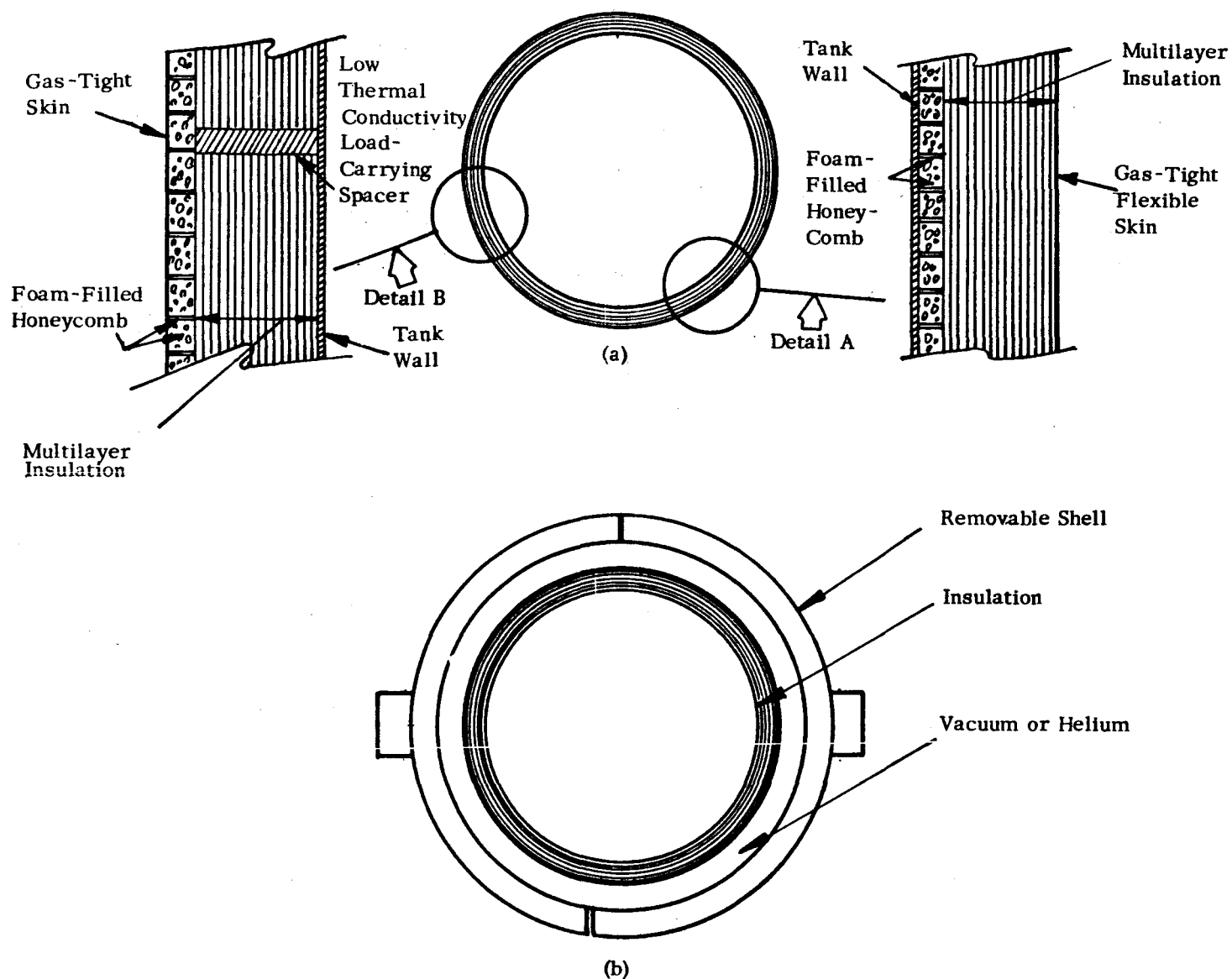


FIGURE VI-D1 TECHNIQUES TO DECREASE BOIL-OFF LOSSES DURING GROUND STANDBY

of foam next to the tank could further reduce these losses and could provide a safety factor in case hydrogen should leak into the insulated space. At high altitudes, the insulation can regain almost all of its high insulating effectiveness if it is not subject to hysteresis effects.

Although this scheme is an attractive one, care has to be taken to achieve tight seals at the many projections caused by supports and piping attachments.

(b) An alternative approach to evacuating insulation on the ground is to provide a light-weight rigid insulating cover capable of supporting limited compressive forces and permitting the insulated space to be filled with helium at a slight overpressure (see Figure VI-D1a, Detail B). The helium prevents air or water vapor from condensing and freezing in the insulation next to the liquid-hydrogen tank. The presence of liquid air, in addition to providing a LOX compatibility hazard, would cause the insulating effectiveness to deteriorate and, upon being heated, could lead to the formation of explosive gases during the boost phase. The cover would aid in preventing damage to the insulation and would be capable of withstanding aerodynamic forces and boost heating conditions. In addition, the multilayer insulation would not be exposed to mechanical loads because any applied loads could be transmitted to the tank wall by load-carrying, low-conductivity spacers.

(c) The alternative to having a flexible shell is an arrangement of clam shells which make a tight seal with the tank. (See Figure VI-D1b.) At the time of the launch, the clam shells are removed. Because of the large size of most tanks, the need to have connections made to the tank during the ground standby period, and the complexity involved in arranging for removable clam shells, this approach is not recommended.

### 3. Boost Phase

Depending upon the trajectory, the aerodynamic heating during the boost phase may lead to temperatures as high as 800°F on the sides of the vehicle. Although this heating effect occurs only for a short time, it can have the following consequences:

(a) The surface layers of the insulation system could be materially degraded because of lack of strength at the high temperatures and the action of aerodynamic forces during this period.

(b) The heat applied could penetrate into the insulation system, depending upon the system's diffusivity and heat capacity, and thus be responsible for stratification of the fuel even after the vehicle has successfully withstood the boost phase.

It is, therefore, desirable to use materials which: (1) can withstand such temperatures without deterioration and are capable of having a coating with a low  $\alpha/\epsilon$  applied to them which can effectively radiate to the surroundings, or (2) can act as effective ablators without a sacrifice in strength properties.

Aerodynamic phenomenon such as boundary layer turbulence, fluctuating wake of drag and flow separation may act on a thermal protection system. In particular, the buffeting forces set up during the boost phase by aerodynamic loads may excite various oscillating frequencies in the tank. The action of these forces on the tank walls has to be established so that the insulation system can be designed to withstand these forces without suffering major damage. It may be useful to arrange for a portion of the insulation system to be jettisoned after the buffeting has subsided, so as to minimize the weight penalty.

### VI-E. LEAK DETECTION TECHNIQUES

Liquid hydrogen, because of its low viscosity, is capable of flows through tiny cracks and imperfections. Because of the difficulties of predicting the location, size, and frequency of leaks, sufficient quantities of liquid hydrogen could escape and lead to: (a) failure of the tank structure, (b) failure of the thermal insulation, (c) intolerable deterioration of the insulating effectiveness of the multilayer insulator, or (d) an explosion hazard.

The liquid hydrogen tank can be treated as if it were a vacuum-type vessel, and it can be subjected to the tests which are common practice in vacuum techniques. Such a procedure can greatly enhance the reliability of the system and permit more accurate predictions of thermal protection system performance.<sup>(19)</sup>

Flaw and leak detection methods, such as ultra-sonic testing, x-ray radiography and helium mass spectrometry, are standard procedures in vacuum technology. The helium mass spectrometer, in particular, should be used to test components, sub-assemblies, and final assembly welds at various stages of the construction process to assure maximum reliability.

Cold leak-testing of critical parts at either liquid nitrogen or liquid hydrogen temperatures is highly recommended, because leaks which cannot be detected while the tank is warm tend to become apparent after the tank has been cooled.

Attention will have to be given to the leak detection procedure after the thermal protection system has been installed, so that any leaks which may occur during static-firing tests or final assembly at the launch site can be detected. The sensitivity of the helium mass spectrometer is sufficient to indicate whether thermal protection performance will be impaired by the presence of a leak. Careful consideration has to be given to methods of applying the helium mass spectrometer so as to check large areas of the tank surface in a reasonable time consistent with conditions prevailing during preflight check-out.

The design of the thermal protection system has to be such as to permit the location and repair of a leak after one has been indicated. If careful attention is not paid to leak detection, the high insulating effectiveness of multilayer insulations may be compromised to such a degree that the insulation can no longer perform its function.

## VII. CONCLUSIONS

The developments carried out in the field of thermal protection systems using various material combinations suitable for multilayer insulations show sufficient progress to make their use for large cryogenic tanks for extended space missions attractive. Many of the missions now contemplated can be achieved only if the high insulation effectiveness measured in the laboratory can be maintained after the thermal protection system has been installed on a tank and subjected to the various phases of space flight.

Before thermal protection systems can be applied routinely to cryogenic tanks, further development is necessary. Based on work already in progress, system design can be established more clearly and the additional efforts required in the various branches of science and technology better defined to meet the objectives of the future space-flight missions.

## APPENDIX A

### SPHERICAL, CYLINDRICAL, AND FLAT PLATE THERMAL CONDUCTIVITY APPARATUS

#### A. SPHERICAL APPARATUS

Figure A-1 shows a spherical thermal conductivity apparatus consisting of an inner sphere filled with a cryogenic liquid and an outer sphere kept at a desired temperature by means of an electrical heater or a constant temperature bath. The test sample is placed between the two spheres. The boil-off rate of the cryogenic liquid is an indication of the heat flow through the material. A variation of this type of apparatus has an electrical heater installed inside the inner sphere while the outer sphere is placed into a cryogenic liquid. The heat input to the heater is used in the calculation of thermal conductivity.

This type of apparatus is simple to construct, and it eliminates edge effects. However, it is difficult to produce a spherically shaped sample, except for loose-fill materials. Moreover, the density of the specimen cannot be easily controlled; only one sample size can be tested; it is difficult to apply mechanical pressure to the sample; and the heat leak along the neck of the inner sphere cannot be easily estimated.

#### B. CYLINDRICAL APPARATUS

Figure A-2 shows a cylindrical thermal conductivity apparatus.<sup>(8)</sup> It consists of a measuring vessel provided with end guard vessels. The upper guard vessel reduces the heat loss through the neck of the measuring vessel. All three vessels are filled with the same cryogenic liquid. The outer jacket can be kept at a uniform temperature by an electrical heater or a constant temperature bath. The boil-off rate of the cryogenic liquid from the measuring vessel is an indication of the heat flow through the sample.

This apparatus has been used for the testing of powders, foams, fibers and multilayer insulations.<sup>(20)</sup> It cannot be easily adapted to measure the influence of thermal conductivity changes caused by mechanical pressure on the sample, because the thickness of the sample cannot be accurately measured. However, it has the advantage that edge effects can be more easily controlled because the distance between the guarded section and the measuring section is comparatively long.

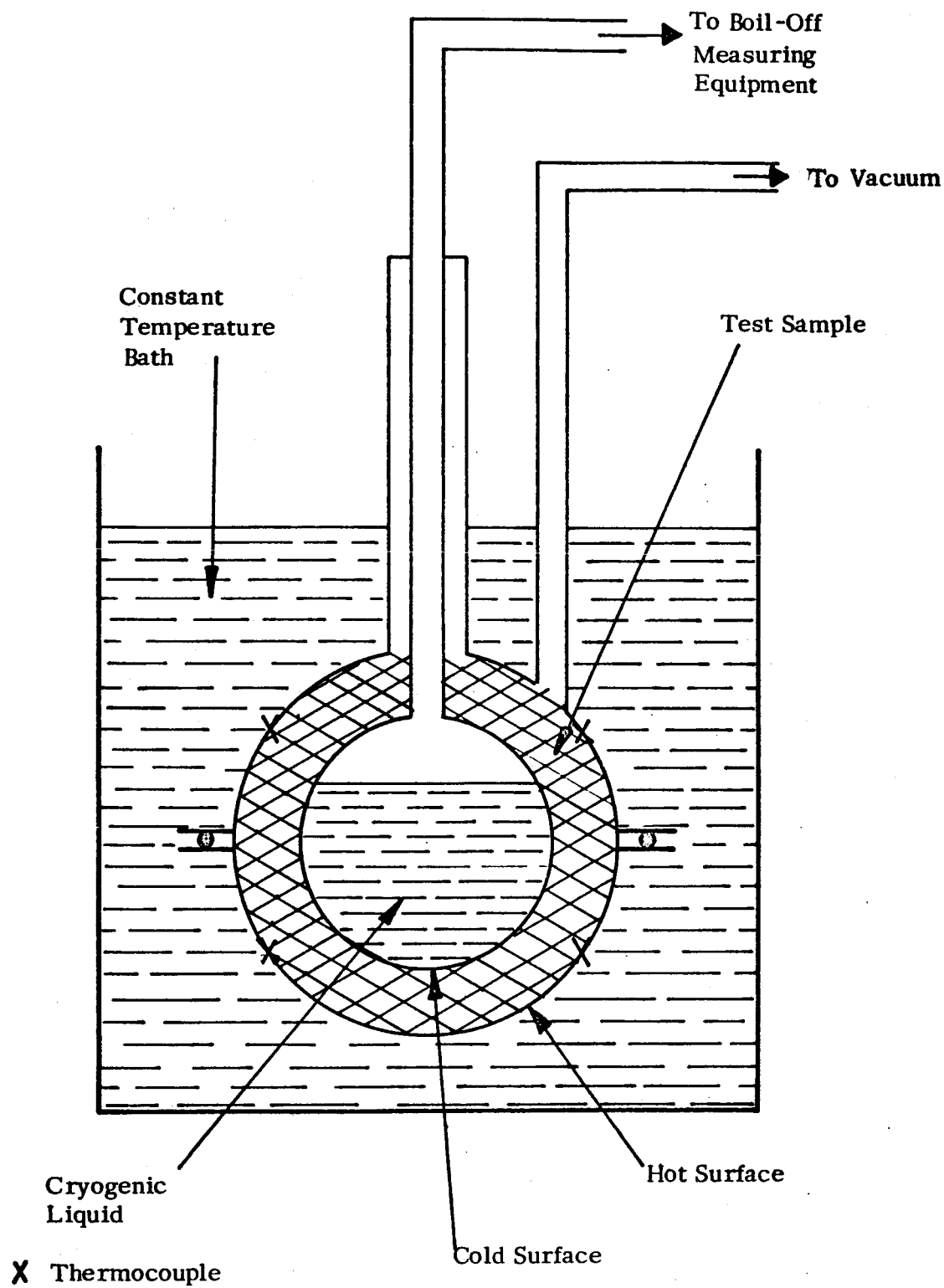
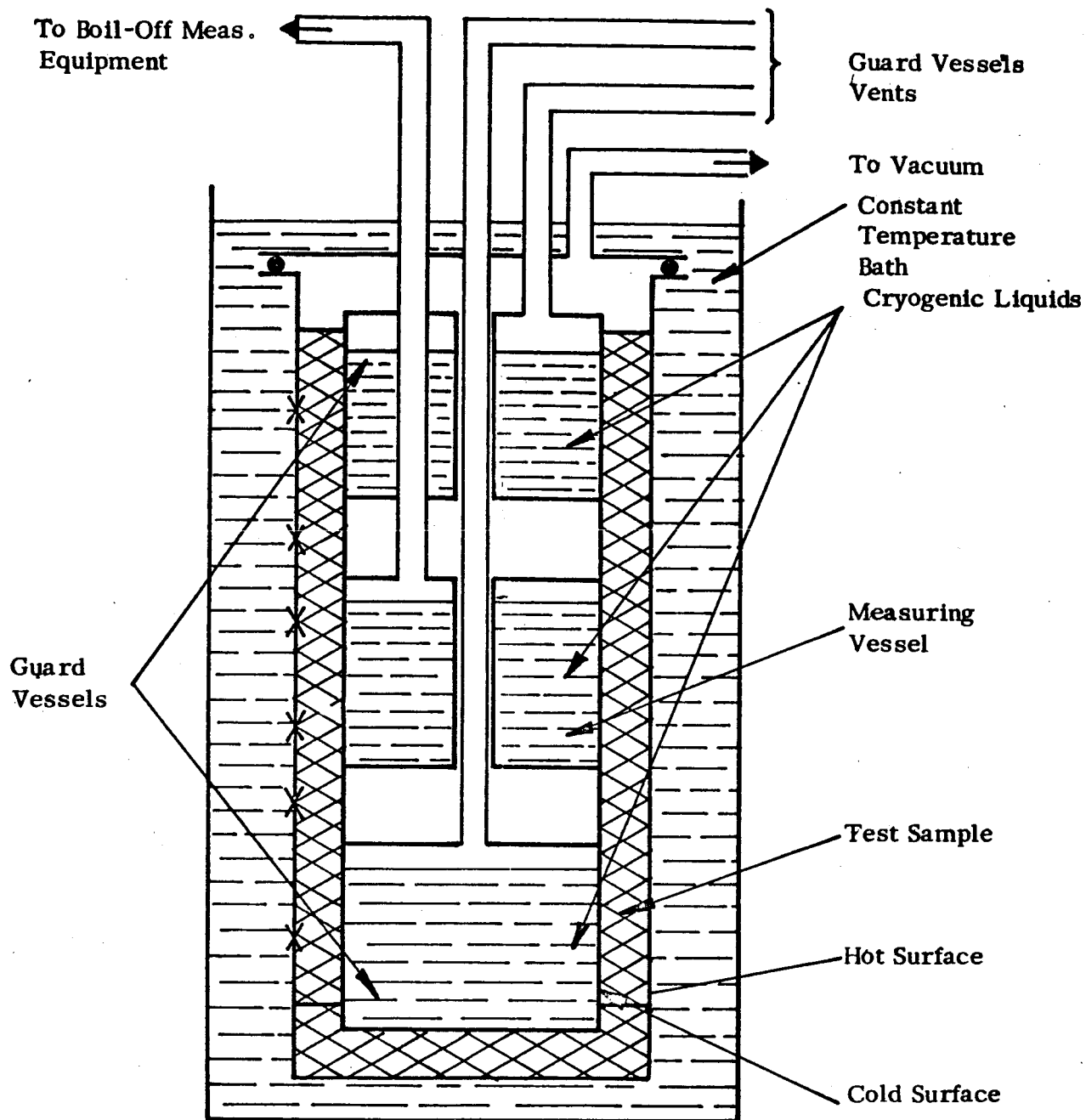


FIGURE A-1 THE SPHERICAL THERMAL CONDUCTIVITY APPARATUS



X Thermocouple

FIGURE A-2 THE CYLINDRICAL THERMAL CONDUCTIVITY APPARATUS

## C. FLAT PLATE APPARATUS

The flat plate thermal conductivity apparatus consists of hot and cold plates between which a sample can be inserted. This type of apparatus approaches closest to the ASTM guarded hot plate apparatus<sup>(21)</sup> in concept and has been shown to be versatile and useful in a number of investigations. The following variations of the apparatus are in use:

### 1. Guarded Hot Plate

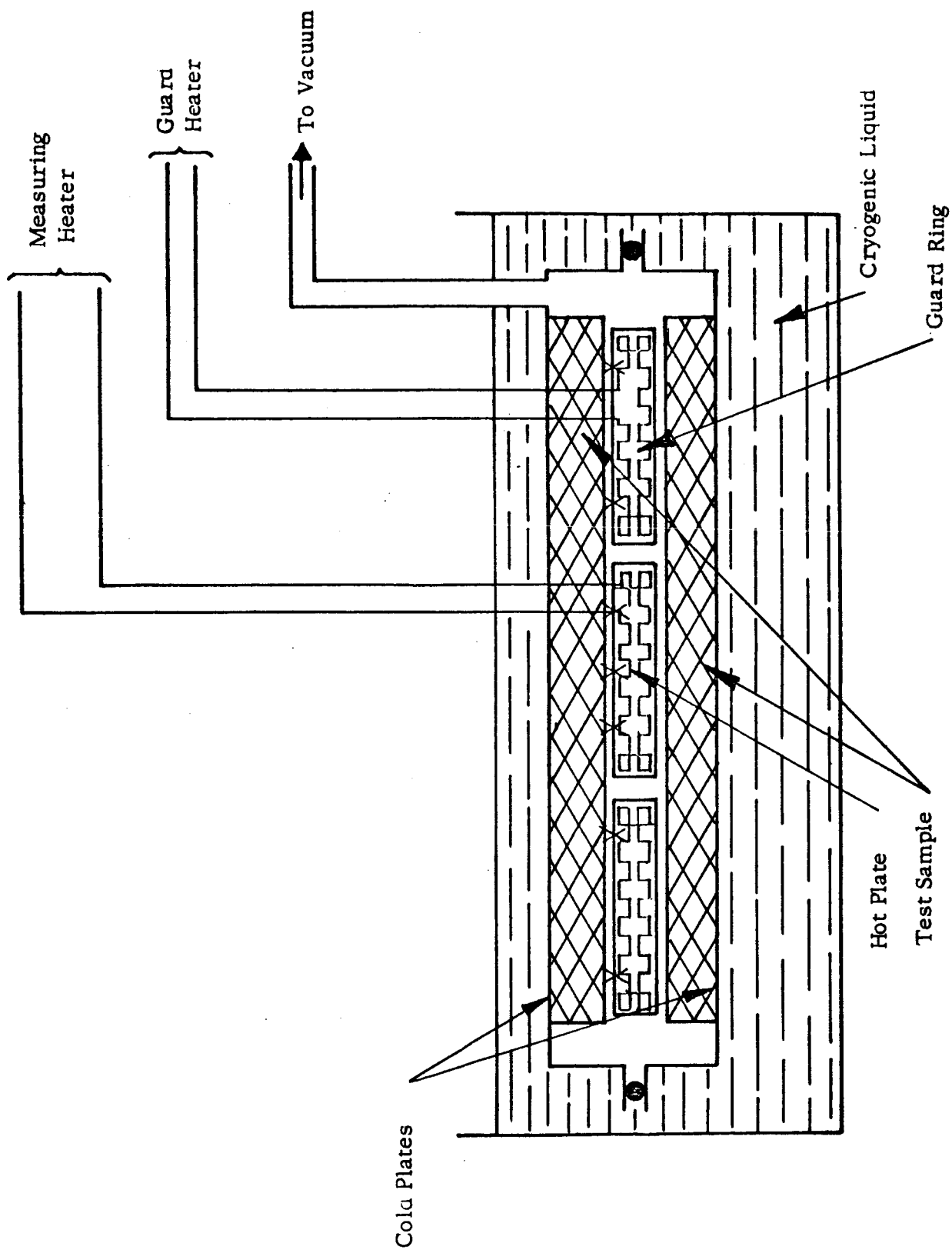
The guarded hot plate apparatus shown in Figure A-3 consists of an electrically heated hot plate placed inside a ring shaped guard heater.<sup>(22)</sup> Two test specimens are placed on each side of the hot plate. The complete assembly is enclosed in a container which can be evacuated and is then immersed in a constant temperature bath. This apparatus permits the measurement of thermal conductivity over an easily adjustable range of temperature. However, the physical environment of the sample tends to be harder to control. This apparatus has been particularly useful in the measurement of the thermal conductivity of foams.

A variation of this type of apparatus is the single-guarded hot plate apparatus shown in Figure A-4.<sup>(23)</sup> Only one sample needs to be installed between the hot plate and the single cold plate. The temperature of the guard ring has to be kept equal to that of the measuring hot plate to prevent heat transfer between guard and measuring plate; otherwise, errors due to the departure from one-dimensional heat flow may be introduced. This problem tends to be accentuated when materials of high insulating effectiveness are used, although it can be overcome by sensitive heater controls.

### 2. Single-Guarded Cold Plate

Figure A-5 shows a single-guarded cold plate apparatus.<sup>(24)</sup> In this apparatus, the bottom of the measuring vessel constitutes the cold plate. The measuring vessel is surrounded by a guard vessel. The hot plate is kept at a desired uniform temperature by a circulating fluid. The boil-off rate of a cryogenic liquid from the measuring vessel is an indication of the heat flow through the sample.

The use of a calibrated heat-flow meter is an alternative method for measuring the heat input into the sample.<sup>(25)</sup> However, calibration of the heat-flow meter, particularly at very low heat flow rates, is difficult.



X Thermocouple

FIGURE A-3 THE GUARDED HOT PLATE THERMAL CONDUCTIVITY APPARATUS

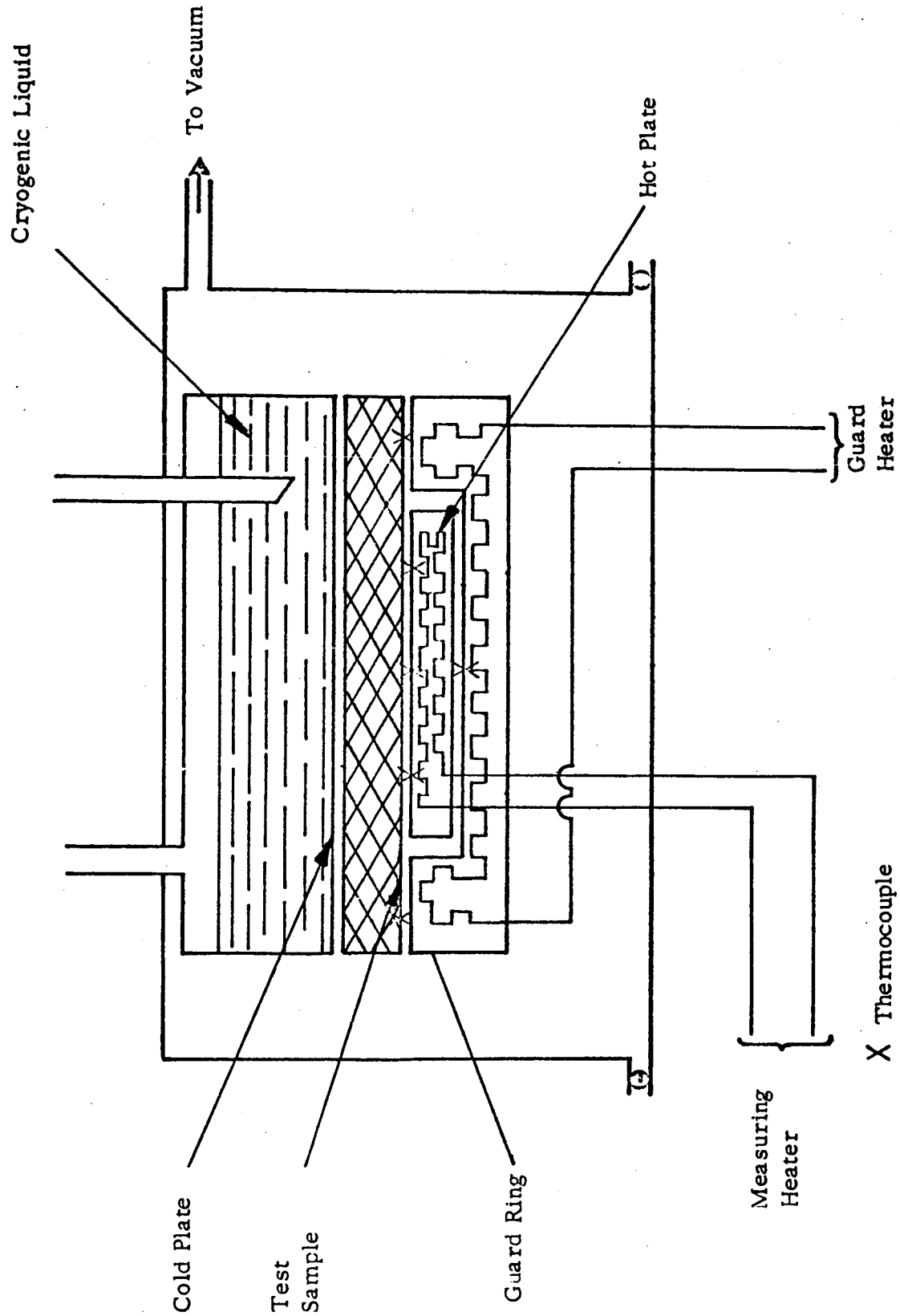


FIGURE A-4 THE SINGLE-GUARDED HOT PLATE THERMAL CONDUCTIVITY APPARATUS

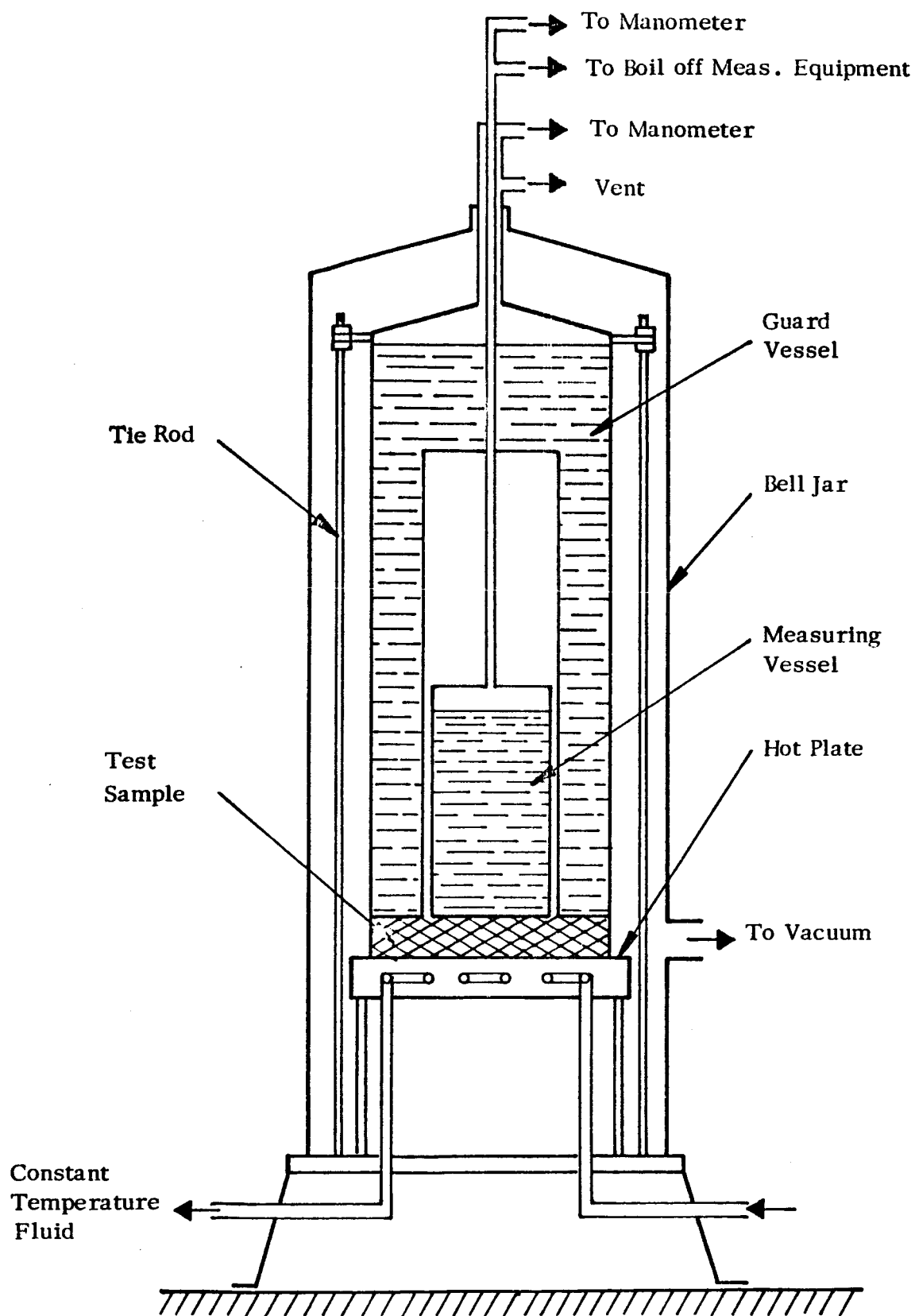


FIGURE A-5 THE SINGLE-GUARDED COLD PLATE THERMAL CONDUCTIVITY APPARATUS

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